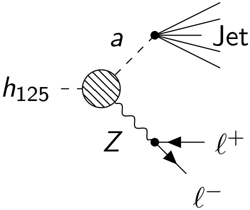
Higgs Boson Decays to Light Scalars at ATLAS

University of Warwick, 18th June 2020

Elliot Reynolds



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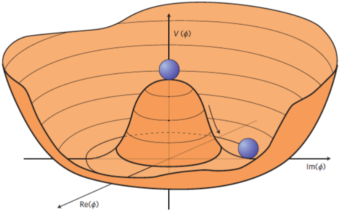
Ways to Extend the Higgs Sector

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 $W_L W_L \rightarrow W_L W_L$



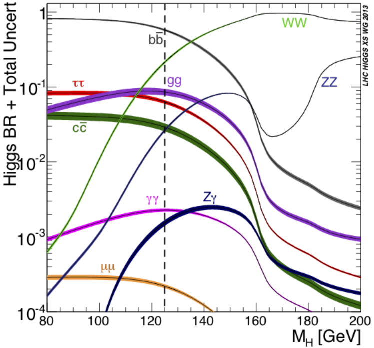
$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1(x) + i\phi_2(x) \\ \phi_3(x) + i\phi_4(x) \end{pmatrix} \longrightarrow$$

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

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

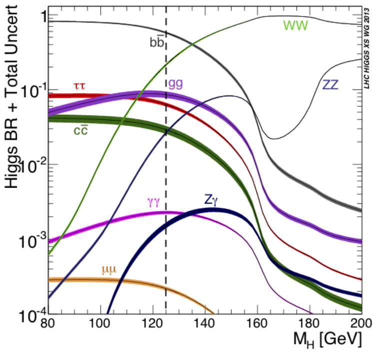
$$m_Z = \frac{1}{2} v \sqrt{g_W^2 + g'^2}$$

Observed Higgs Boson



arXiv:1307.1347

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



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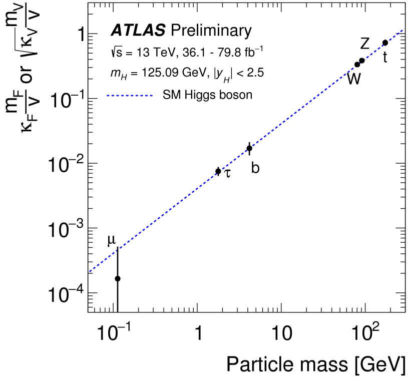

ATLAS-CONF-2018-031

Extended Higgs Sectors

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- Simplest extensions to the SM Higgs sector:
  - 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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  - Two Higgs doublet model (2HDM)
  - 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

- The 2HDM has a pair of scalar doublet fields
- 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)

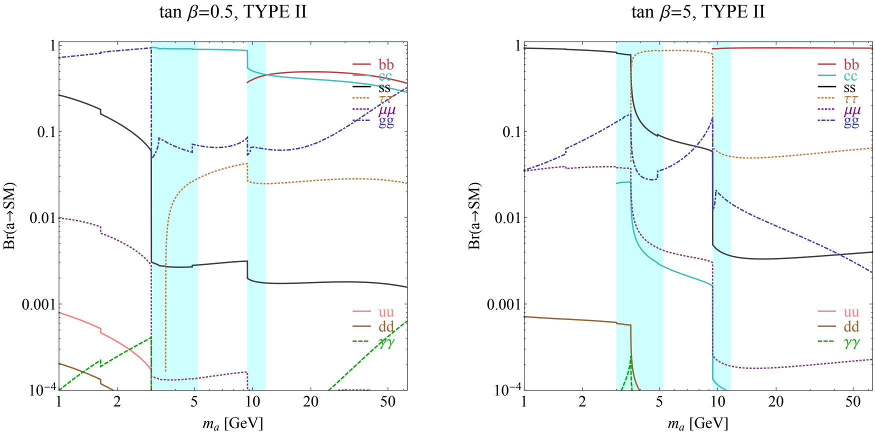
2HDM Type	First Doublet	Second Doublet
Type-I	All fermions	
Type-II (Supersymmetry)	Up-type fermions	Down-type fermions
Type-III	Quarks	Leptons
Type-IV	Up-type quarks	Down-type quarks
	Down-type leptons	Up-type leptons

Two Higgs Doublet Model with an Additional Singlet

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

Type-II 2HDM+S BR($a \to$ SM)

arXiv:1312.4992



Heavy or Light?

The new scalars can be heavy...

- Many active search channels:
  - $H \to \tau\tau$ (arXiv:2002.12223)
  - $H \to \mu\mu$ (arXiv:1901.08144)
  - $H \to WW$ (arXiv:1710.01123)
  - $H \to \gamma\gamma$ (arXiv:1707.04147)
  - $bH \to bbb$ (arXiv:1907.02749)
  - $H^{\pm} \to tb$ (arXiv:1808.03599)
  - $H^{\pm} \to \tau\nu$ (arXiv:1807.07915)
  - $H^{\pm} \to ZW$ (arXiv:1806.01532)
  - $H^{\pm\pm} \to W^{\pm}W^{\pm}$ (arXiv:1808.01899)
- They could be too heavy to be produced at the LHC

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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

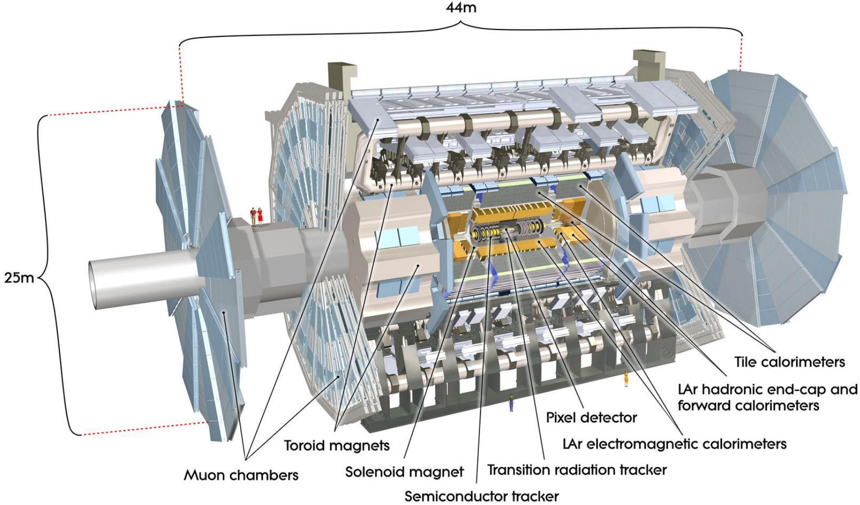
- Small natural width of h_{125} means even small couplings to new light resonances would lead to large BRs

Current ATLAS Search Programme

(Selection of Searches)

ATLAS Detector

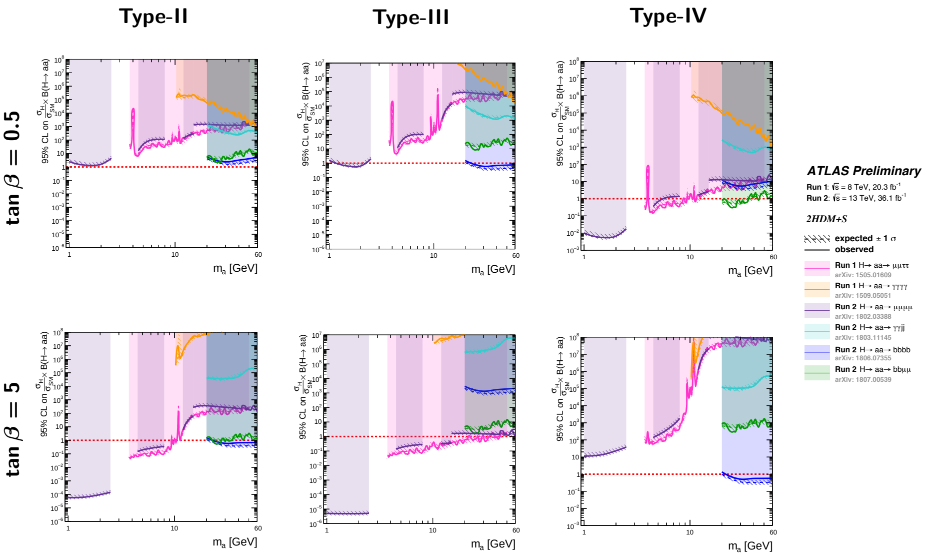
LHC: 13 TeV *pp* collisions. Run 2: $\mathcal{L}_{\text{int}} = 139\ \text{fb}^{-1}$ to date



arXiv:1011.6665

ATLAS 2HDM+S $h_{125} \to aa$ Summary Plots

ATL-PHYS-PUB-2018-045

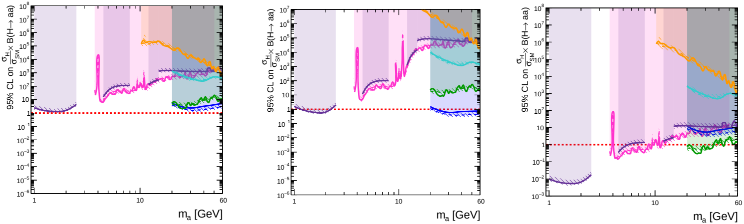


ATLAS 2HDM+S $h_{125} \to aa$ Summary Plots

ATL-PHYS-PUB-2018-045

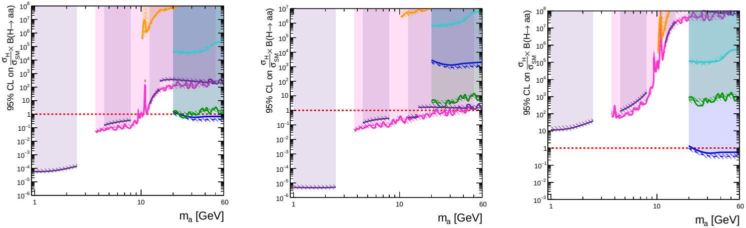
Type-II **Type-III** **Type-IV**

$\tan\beta = 0.5$



Very few $h_{125} \to Za$ decays modes!

$\tan\beta = 5$



ATLAS 2HDM+S $h_{125} \to aa$ Summary Plots

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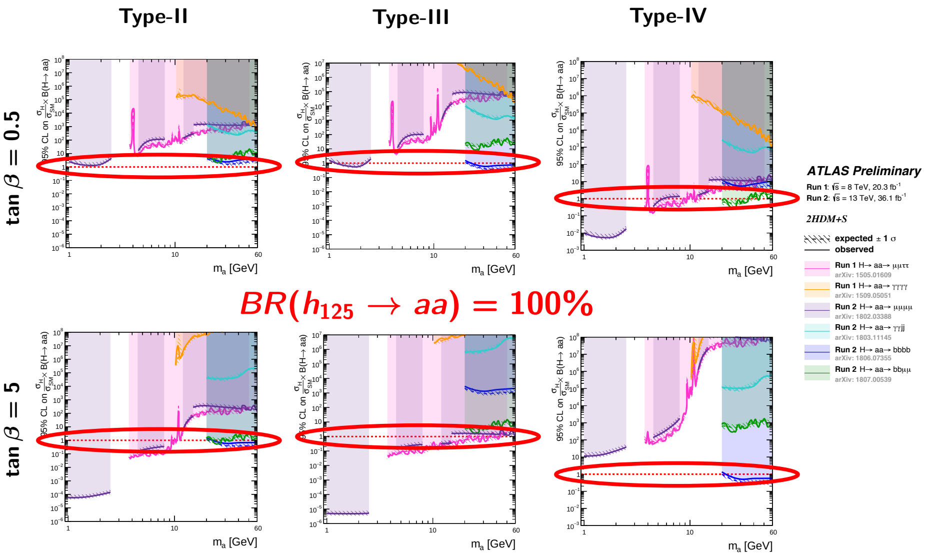

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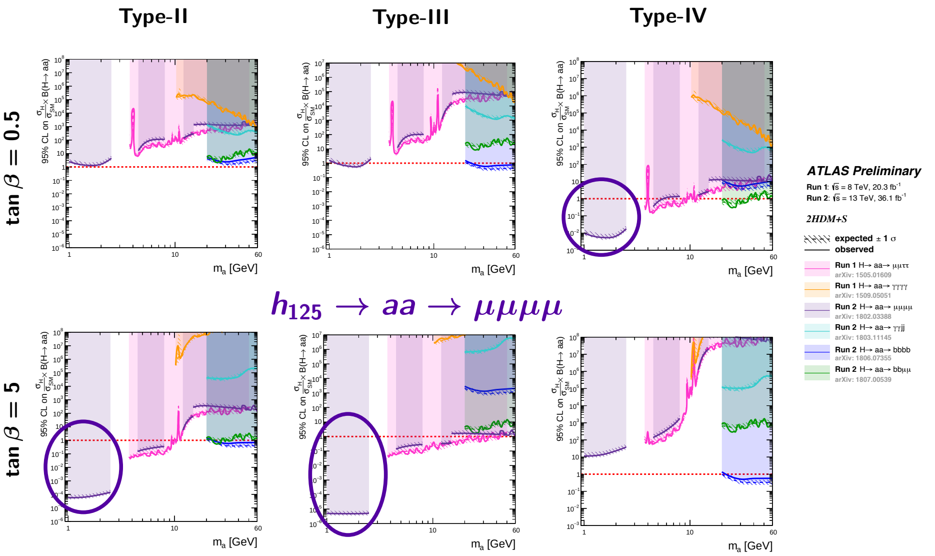
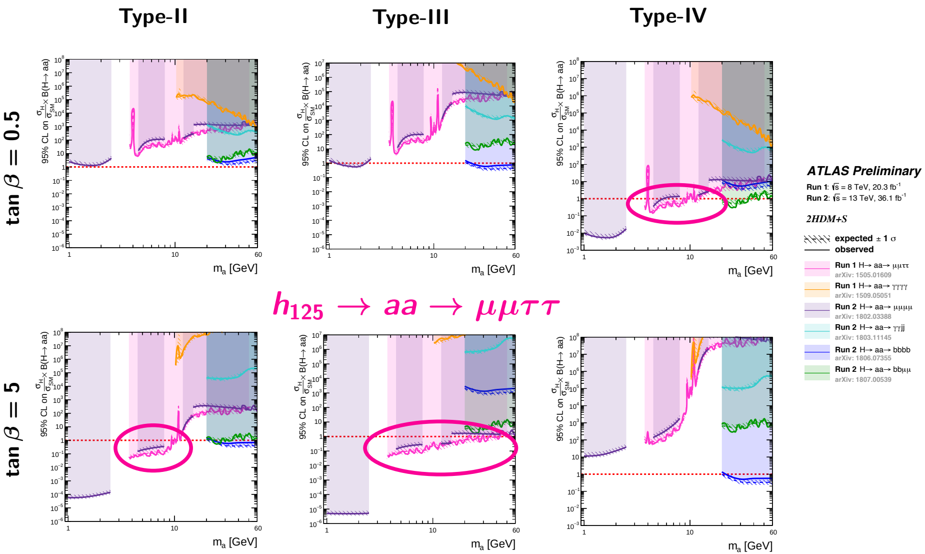
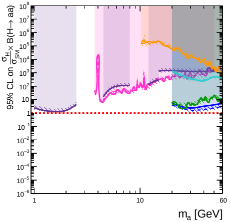
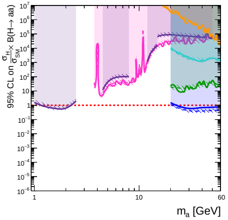
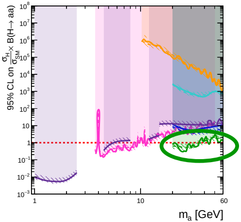
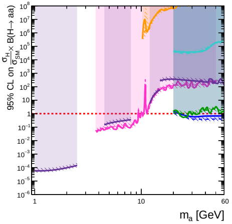
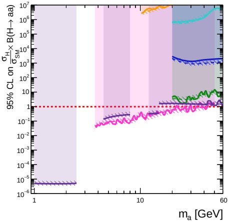
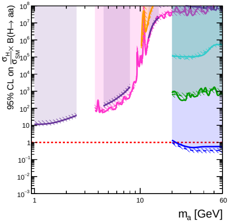




Type-II
Type-III
Type-IV
tan β = 0.5
tan β = 5
$h_{125} \to aa \to \mu\mu\tau\tau$
95% CL on σH/σSM × B(H→ aa)
m_a [GeV]
ATLAS Preliminary
Run 1: √s = 8 TeV, 20.3 fb⁻¹
Run 2: √s = 13 TeV, 36.1 fb⁻¹
2HDM+S
expected ± 1 σ
observed
Run 1 H→ aa→ μμττ
arXiv: 1505.01609
Run 1 H→ aa→ γγγγ
arXiv: 1509.05051
Run 2 H→ aa→ μμμμ
arXiv: 1802.03388
Run 2 H→ aa→ γγjj
arXiv: 1803.11145
Run 2 H→ aa→ bbbb
arXiv: 1806.07355
Run 2 H→ aa→ bbμμ
arXiv: 1807.00539

ATLAS 2HDM+S $h_{125} \to aa$ Summary Plots

ATL-PHYS-PUB-2018-045

	Type-II	Type-III	Type-IV
tan β = 0.5			
tan β = 5			

$h_{125} \to aa \to bb\mu\mu$

ATLAS Preliminary

Run 1: √s = 8 TeV, 20.3 fb⁻¹

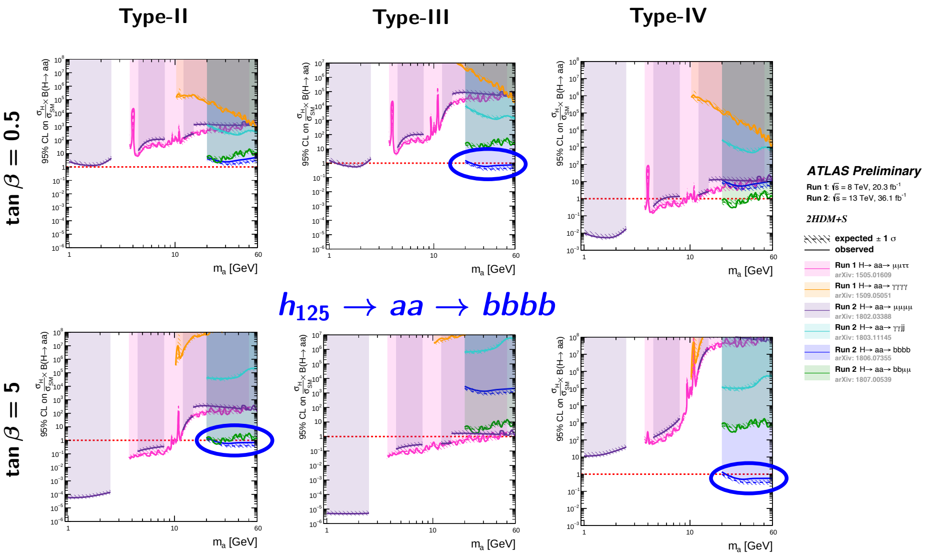
Run 2: √s = 13 TeV, 36.1 fb⁻¹

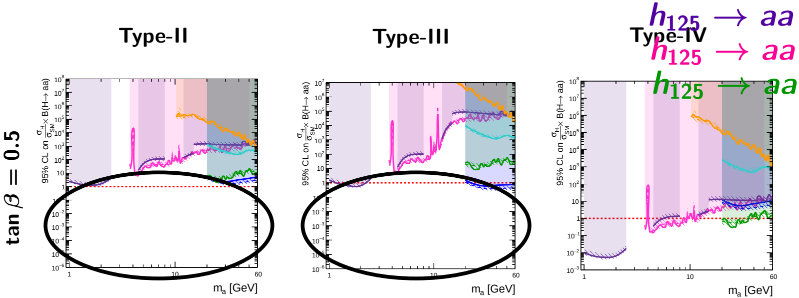
2HDM+S

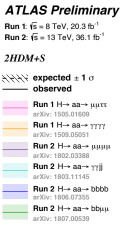
- **expected** ± **1** σ
- **observed**
- **Run 1** H→ aa→ μμττ — arXiv: 1505.01609
- **Run 1** H→ aa→ γγγγ — arXiv: 1509.05051
- **Run 2** H→ aa→ μμμμ — arXiv: 1802.03388
- **Run 2** H→ aa→ γγjj — arXiv: 1803.11145
- **Run 2** H→ aa→ bbbb — arXiv: 1806.07355
- **Run 2** H→ aa→ bbμμ — arXiv: 1807.00539

ATLAS 2HDM+S $h_{125} \rightarrow aa$ Summary Plots

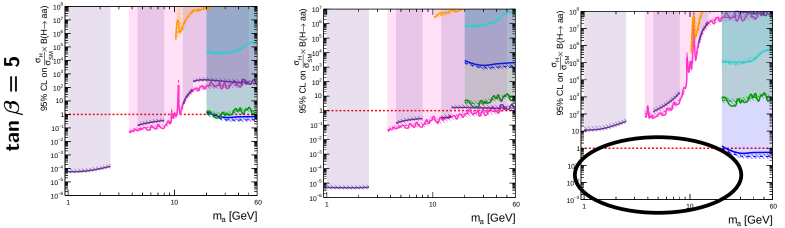
ATL-PHYS-PUB-2018-045







$\tan\beta$ suppression of down-type lepton couplings!



ATLAS 2HDM+S $h_{125} \to aa$ Summary Plots

ATL-PHYS-PUB-2018-045

Type-II	Type-III	Type-IV

$h_{125} \to aa \to bb\mu\mu$

$h_{125} \to aa \to bbbb$

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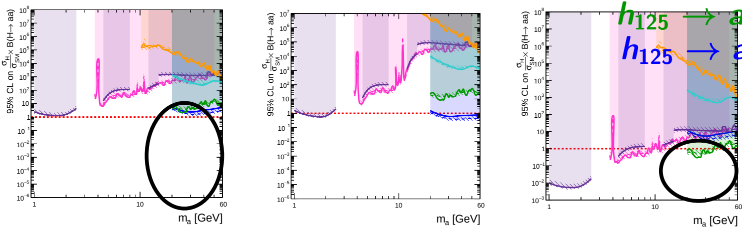
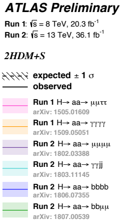
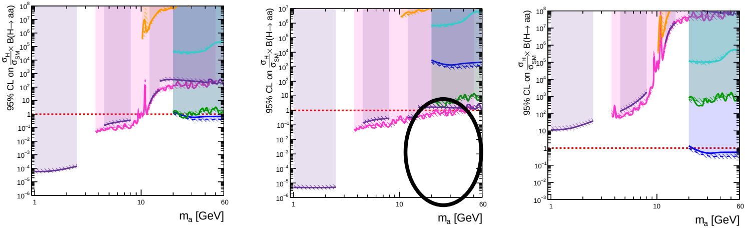




$\tan\beta$ suppression of down-type quark couplings!

$\tan\beta = 5$



$h_{125} \to aa \to \mu\mu\mu\mu$
$h_{125} \to aa \to \mu\mu\tau\tau$
$h_{125} \to aa \to bb\mu\mu$
$h_{125} \to aa \to bbbb$

Type-II **Type-III** **Type-IV**

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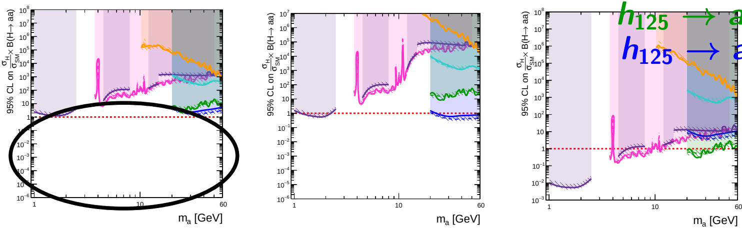

$\tan\beta$ suppression of down-type fermion couplings!

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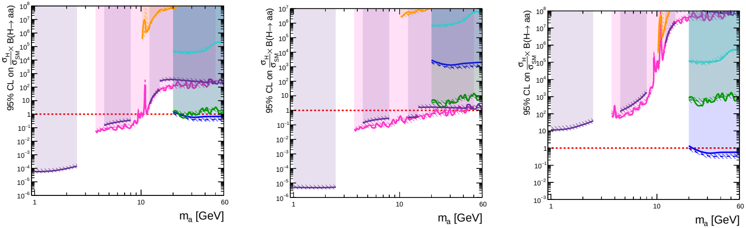

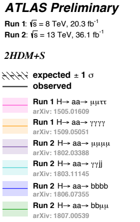

ATLAS 2HDM+S $h_{125} \to aa$ Summary Plots

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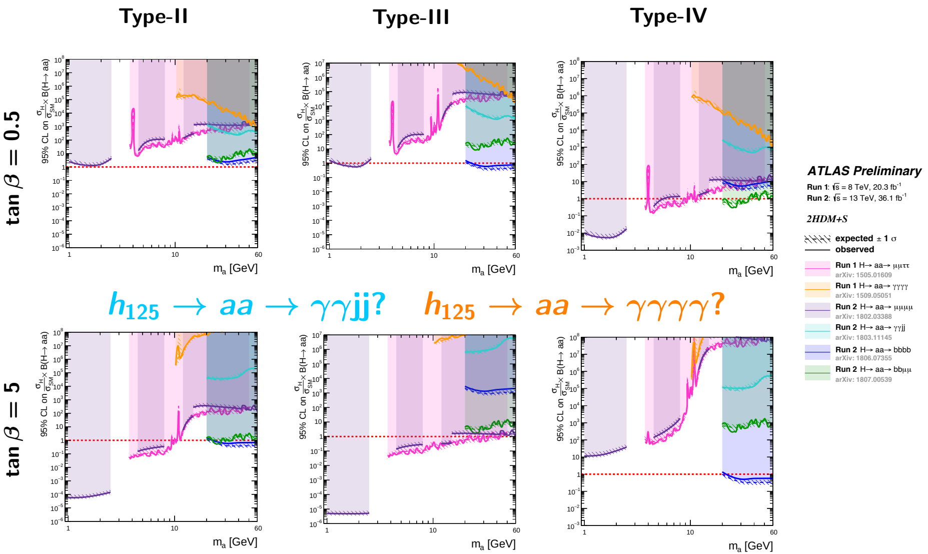
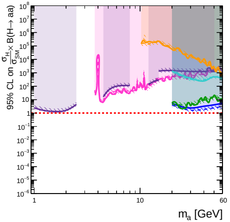
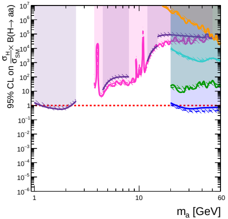
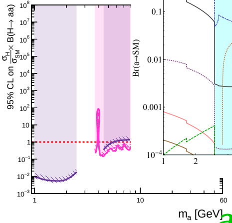


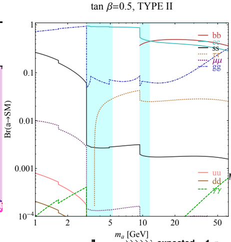
Type-II **Type-III** **Type-**

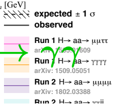
$\tan\beta = 0.5$







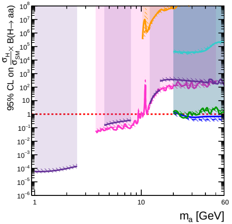


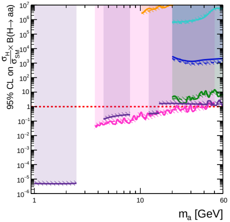


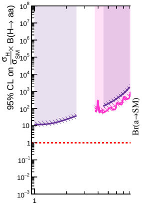
$a \to \gamma\gamma$

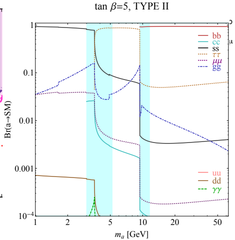
$h_{125} \to aa \to \gamma\gamma jj$? **$h_{125} \to aa \to \gamma\gamma\gamma\gamma$?**

$\tan\beta = 5$









New Ideas Required!

- Very few searches for $h_{125} \to Za$
- Most searches for a use its decays to down-type fermions
- Both gaps can be filled with a search for $\boldsymbol{h_{125} \to Za \to \ell\ell j}$
- Major challenge from overwhelming $Z +$ jets background
- New ideas required to address this...

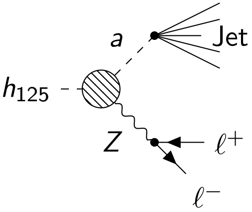
$$h_{\mathbf{125}} \to Za \to \ell\ell\mathbf{j}$$

arXiv:2004.01678 and Auxiliary Material

Aims and Motivation

Aims

- Use full ATLAS Run II dataset (139 fb^{-1}) to perform first search for $\boldsymbol{h_{125} \to Z(\ell^+\ell^-)a/\mathcal{Q}(\text{had})}$, $\ell = e$ *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 constraints 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**) a signals
  - Higher BR to light hadrons and unique decay kinematics
- Signals from inclusive Higgs boson production
- Dominant background: $\boldsymbol{Z +}$ **jets**
  - 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 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, radius parameter 0.4, formed of calorimeter clusters, $p_\mathrm{T} > 20$ 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 $< m_{\ell^+\ell^-\mathrm{j}} <$ 135 GeV

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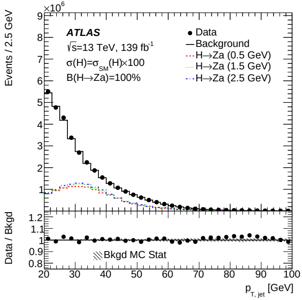
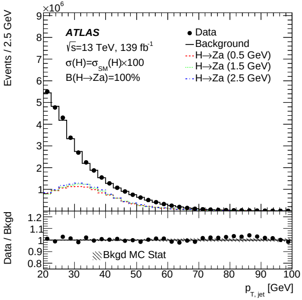
Pre-Higgs	$m_{\ell^+\ell^-\mathrm{j}} < 250$ GeV
Select highest p_T jet as a-candidate	
$\geq$ 2 tracks	$\geq$ 2 tracks ghost associated to the calo jet
Higgs SR	120 GeV $< m_{\ell^+\ell^-\mathrm{j}} <$ 135 GeV



Event 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, radius parameter 0.4, formed of calorimeter clusters, $p_{\mathrm{T}} > 20$ 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 $< m_{\ell^+\ell^-\mathrm{j}} <$ 135 GeV

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Leptons	$N_\ell \geq 2$ with $p_T > 18$ GeV
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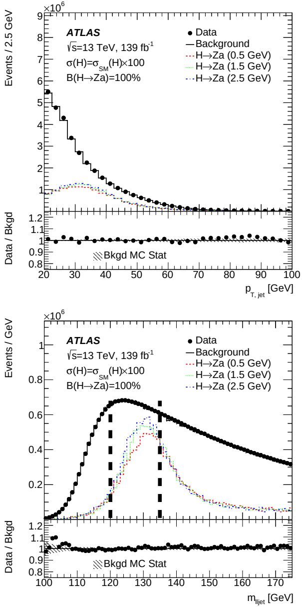
Jet (*a*)	Anti-k_T jet, radius parameter 0.4, formed of calorimeter clusters, $p_T > 20$ GeV
Pre-Higgs	$m_{\ell^+\ell^-j} < 250$ GeV
Select highest p_T jet as *a*-candidate	
≥ 2 tracks	≥ 2 tracks ghost associated to the calo jet
Higgs SR	120 GeV $< m_{\ell^+\ell^-j} <$ 135 GeV



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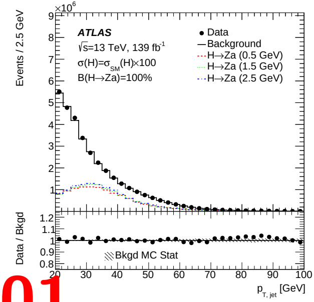
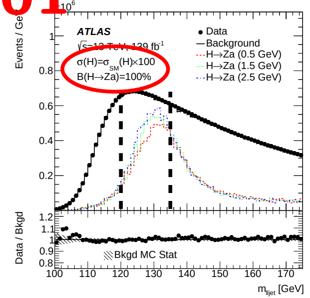
Pre-Higgs	$m_{\ell^+\ell^- \mathrm{j}} < 250$ GeV
Select highest p_T jet as a-candidate	
≥ 2 tracks	≥ 2 tracks ghost associated to the calo jet
Higgs SR	120 GeV $< m_{\ell^+\ell^- \mathrm{j}} <$ 135 GeV

$S/B < 0.01$



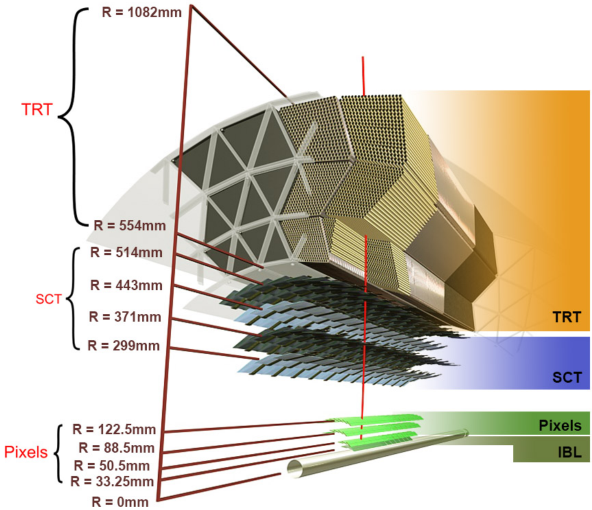


Hadronic Resonance Tagger (1/6)

- Subtle differences in substructure of *a*-induced and QCD-induced jets
- Substructure techniques commonplace for high-mass resonances, using wide jets and calorimeter information
- **Can similar techniques be applied using thin jets?**

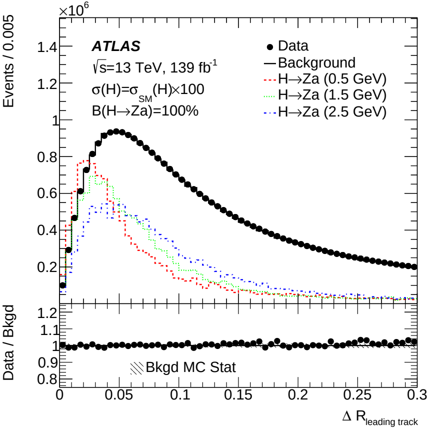
Pixel resolution
$\sim 12\mu m$ in $R - \phi$ and ~ 66 (~ 77) μm in z (R) in the barrel (disks)

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

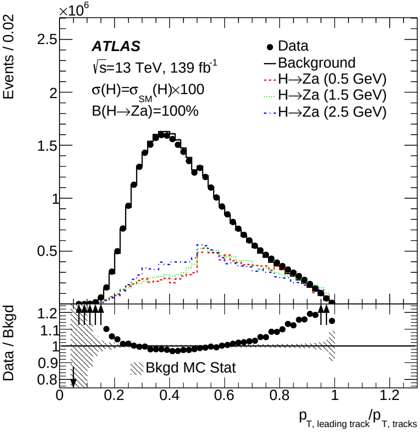


arXiv:1011.6665

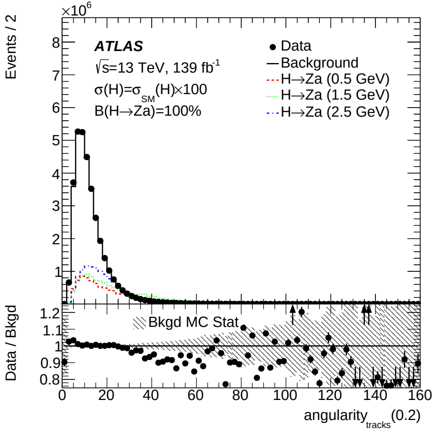
- Input variables:
  1. $\Delta R_{\text{lead track}}$



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

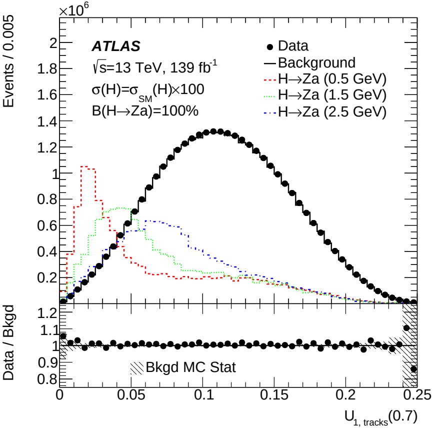


- Input variables:
  1. $\Delta R_{\text{lead track}}$
  2. $p_{\text{T, lead track}} / p_{\text{T, tracks}}$
  3. angularity(2)[†]



† arXiv:0807.0234

- Input variables:
  1. $\Delta R_{\text{lead track}}$
  2. $p_{\text{T, lead track}} / p_{\text{T, tracks}}$
  3. angularity(2)†
  4. $U1(0.7)$‡



† arXiv:0807.0234

‡ arXiv:1609.07483

- Input variables:
  1. $\Delta R_{\text{lead track}}$
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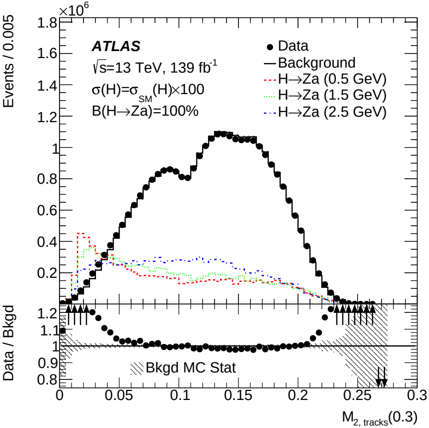
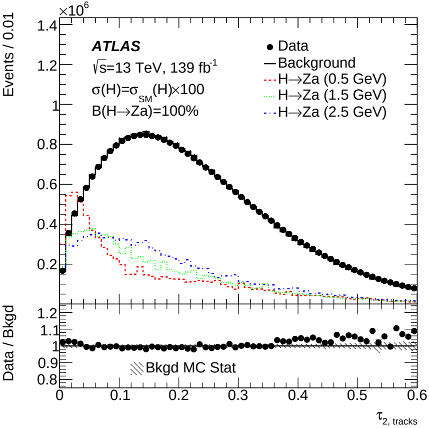
  4. $U1(0.7)$‡
  5. $M2(0.3)$‡



† arXiv:0807.0234

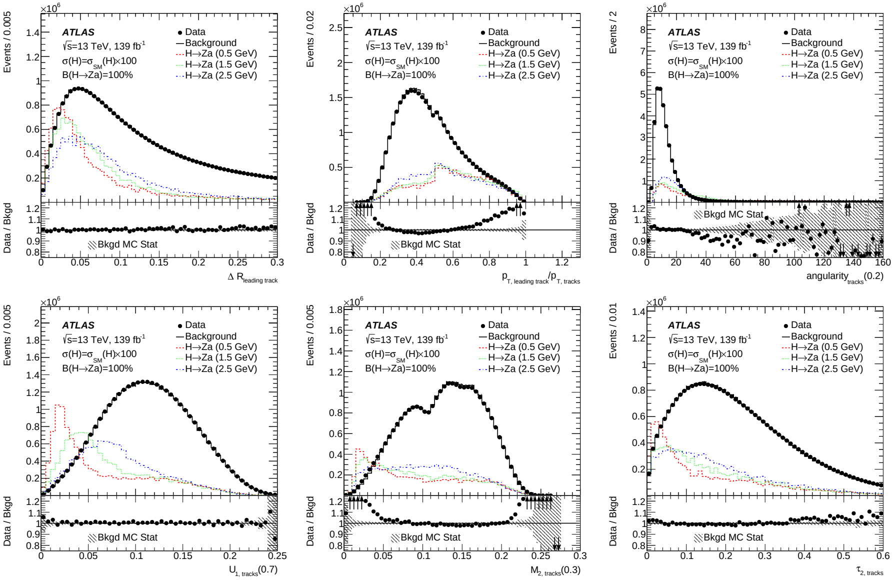
‡ arXiv:1609.07483

- Input variables:
  1. $\Delta R_{\text{lead track}}$
  2. $p_{\text{T, lead track}} / p_{\text{T, tracks}}$
  3. angularity(2)[†]
  4. $U1(0.7)$[‡]
  5. $M2(0.3)$[‡]
  6. τ_2[§]

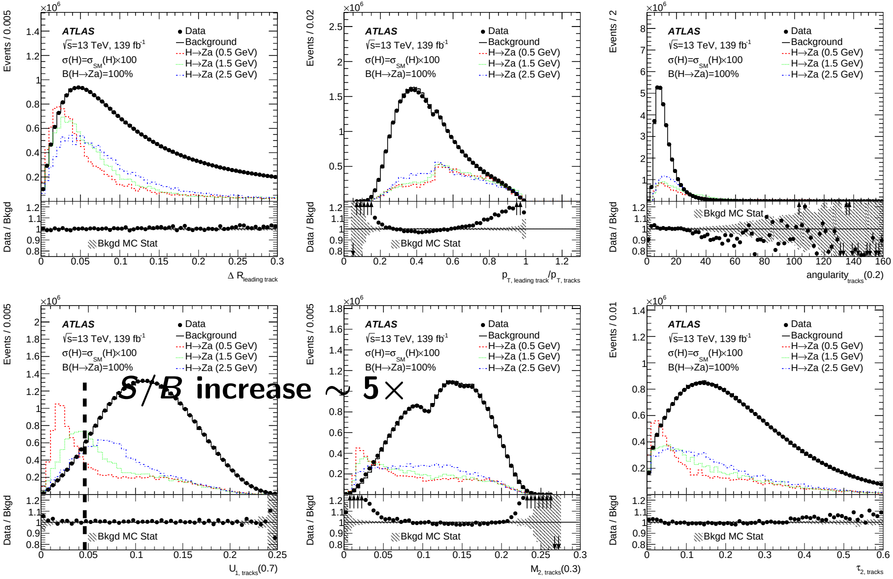


† arXiv:0807.0234 ‡ arXiv:1609.07483 § arXiv:1011.2268

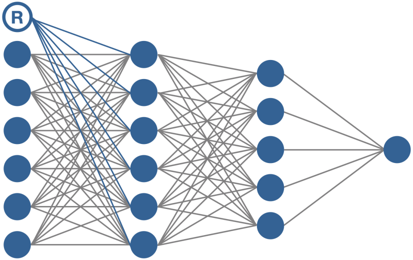
Hadronic Resonance Tagger (3/6) - Substructure Variables



Hadronic Resonance Tagger (3/6) - Substructure Variables

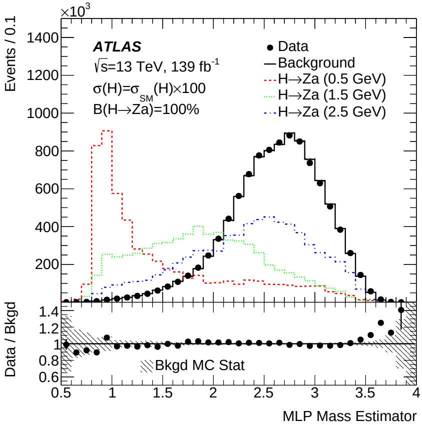


- A Multi-Layer-Perceptron (MLP) is used to combine the substructure variables into a single classifier variable
- An MLP is machine-learning algorithm: a function, with many free parameters, which are fixed during “training”

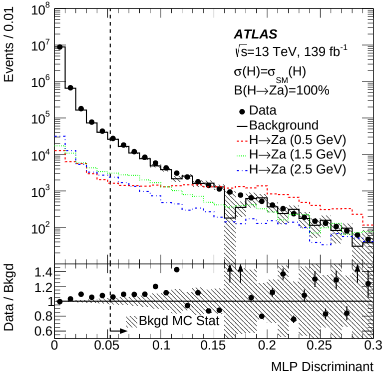


Hadronic Resonance Tagger (5/6) - Regression

- Not a standard classification problem, due to the spectrum of signals
- Solved by training a regression MLP to predict m_a
- m_a hypothesis informs classifier which part of the mass space to consider
- $\sim$ **13%** improvement in the expected $S/\sqrt{B}$



Hadronic Resonance Tagger (6/6) - Classification



- Cut chosen to optimise $S/\sqrt{B}$, assuming all a masses equally likely: $MLP > 0.052$

- Bkgd eff = **0.761%** (MLP)

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} & $U1(0.7)$

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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:

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

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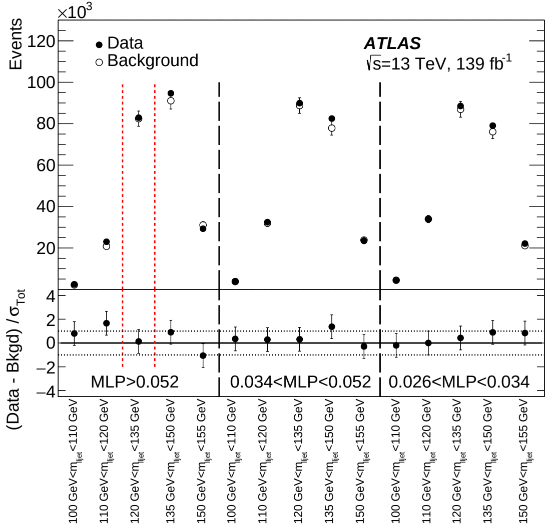
$$A_{\mathrm{SR}}^{\mathrm{ABCD\ Est.}} = \underbrace{\frac{B_{\mathrm{data}}C_{\mathrm{data}}}{D_{\mathrm{data}}}}_{\text{Data-driven ABCD Estimate}} \times \underbrace{\frac{A_{\mathrm{MC}}}{\frac{B_{\mathrm{MC}}C_{\mathrm{MC}}}{D_{\mathrm{MC}}}}}_{\text{MC-based ABCD Correction Factor}}$$

- 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



Statistical Interpretation

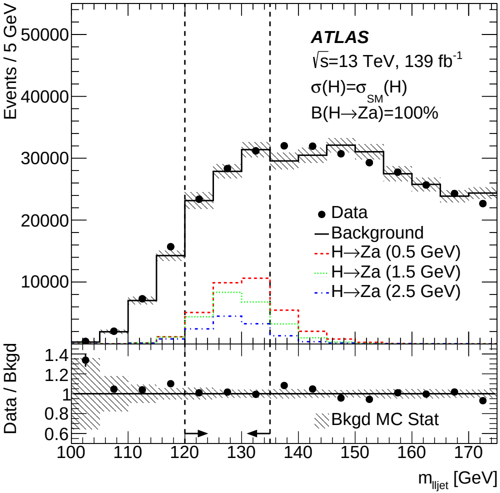
- Single-bin **cut-and-count** analysis strategy adopted
- Expected background:
  - Efficiency: $(8.45 \pm 0.22) \times 10^{-5}$
  - Yield: 82400 ± 2900

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

$\boldsymbol{MLP > 0.052}$

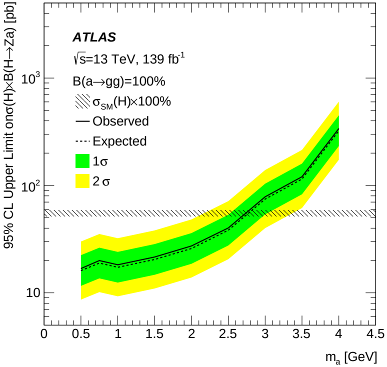


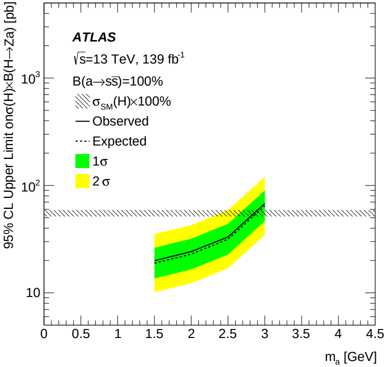
Background: 82400 ± 3700

Observed events: 82908

Model-Independent Limits

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





Outlook and Conclusion

$h_{125} \to Za$ Uncertainty Breakdown

Impact of uncertainties on $\sigma(pp \to h_{125})\text{BR}(h_{125} \to Za)$/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

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Not ATLAS work

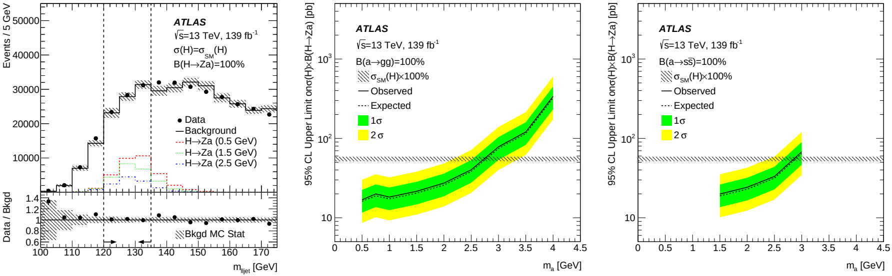
Relevant uncertainties combined in quadrature, and limits on $\sigma(pp \to h_{125})\mathrm{BR}(h_{125} \to Za)/\sigma_{\mathrm{SM}}(pp \to h_{125})$ scaled down linearly, assuming $\mathrm{BR}(a \to gg) = 100\%$

MC Stat	Modelling	0.5 GeV	1.5 GeV	2.5 GeV
✓	✓	31%	39%	72%
✗	✓	20%	26%	46%
✗	✗	7.5%	8.3%	9.7%

How to Generate Enough MC?

- **Generate 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 discriminate the generated data from 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 hadronic resonance identification
- Limits set, starting at BR of **31%**
- This fills in two gaps in the previous search programme: small BR($h_{125} \to aa$), and suppression of a decays to down-type fermions

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

Hadronic Resonance Tagger - ROC Curve