Search for exotic Higgs decays $H \rightarrow aa$ and $H \rightarrow a_1a_2$ in the $4b$ and $6b$ final states using the ATLAS Detector

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ATLAS EXPERIMENT

IFAE Institut de Física d'Altes Energies

EXCELENCIA SEVERO OCHOA

UAB Universitat Autònoma de Barcelona

L International Meetings on Fundamental Physics and XV CPAN Days

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- Event selection
- Background modelling
- Analysis strategy
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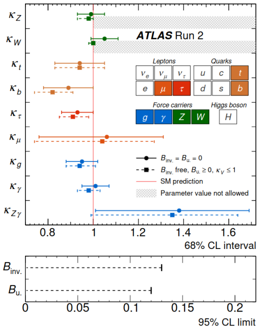
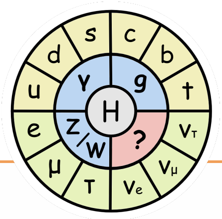
Introduction

[arXiv:2207.00092]

- The SM **Higgs boson (*H*)** is one of the main interests of the LHC Physics Program.
- Until now, its properties are **consistent** with the SM predictions.
- However, available measurements only constrain **non-SM decays to be $\lesssim$ 12%.**



- Non-SM decays of the Higgs boson are not discarded $\Rightarrow$ lots of possibilities for new Physics!
- Example: a new **light spin-0 particle (*a*) with Yukawa-like couplings to SM fermions**.
  - ▹ Could be a DM mediator.
  - ▹ It could make the EW Phase Transition first order $\rightarrow$ EW baryogenesis.
  - ▹ It could solve the naturalness problem.



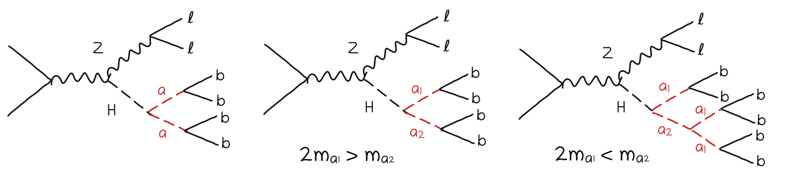
Introduction

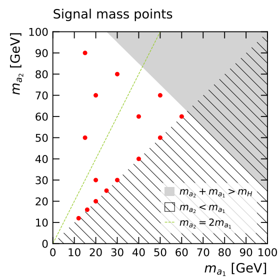
- In this analysis, two options are considered:

  1) **One spin-0 particle a with $2m_a < m_H \Rightarrow$** $\boxed{H \to aa \to 4b}$

  2) **Two spin-0 particles a_1, a_2 with $m_{a_1} + m_{a_2} < m_H \Rightarrow$** $\boxed{H \to a_1 a_2 \to 4b/6b}$

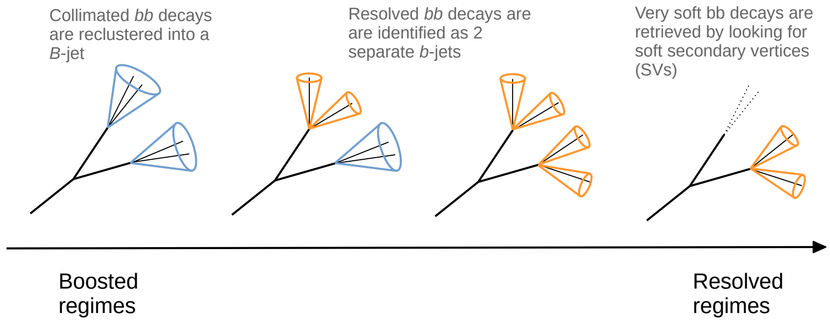
- The *bb* decay channel is chosen to maximise the BR.
- The Higgs boson is produced in association with a Z boson that decays leptonically $\Rightarrow$ less QCD background.

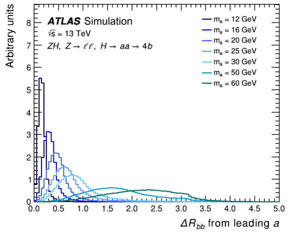




Introduction

- All the mentioned processes have one thing in common: **multi-*b* final state**.
- These *b* behave differently depending on whether the *a* boson is lighter (**boosted regime**) or heavier (**resolved regime**).
- Three types of *b*-object are defined: ***B*-jets, *b*-jets and soft secondary vertices (SVs)**.





Event selection

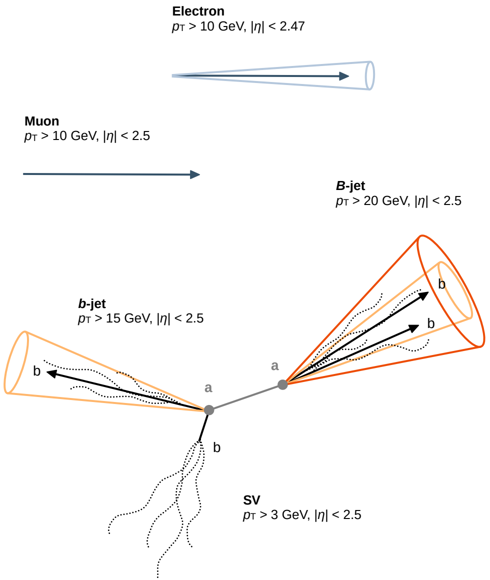
Input events

- Full Run 2 dataset (2015-2018).
- 140 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV recorded using the ATLAS Detector.
- Trigger requirements: at least one lepton (e or μ).

Event selection

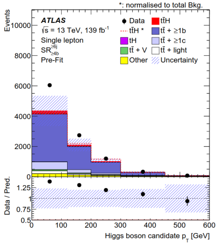
- Exactly two leptons (ee or $\mu\mu$) with $|m_{\ell\ell} - m_Z| \leq 20$ GeV.
- Leading ℓ $p_T > 27$ GeV, sub-leading ℓ $p_T > 10$ GeV.
- At least 3 b-objects:

$$(2 \times N_{B\text{-jets}} + N_{b\text{-jets}} + N_{\text{SVs}}) \geq 3$$

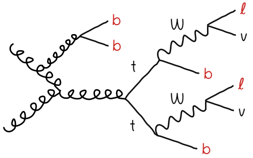


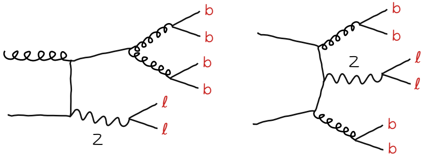
Background modelling

Data vs. MC discrepancies in $tt{+}\geq 1b$ from the $ttH(bb)$ analysis [arXiv:2111.06712]

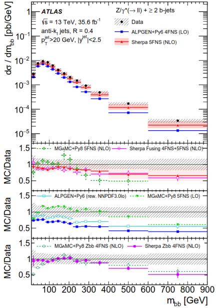


- The two main backgrounds are ***tt*+jets** (left) and ***Z*+jets** (right) with additional b radiation.



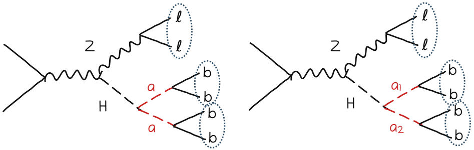


m_{bb} mismodelling in $Z{+}bb$ production [arXiv:2003.11960]



- These backgrounds are **mismodelled** in the MC predictions, with large differences between different generators.
- They are corrected by **comparing to data in signal-depleted regions**.
- Common variables used are the event rate, the number of jets and the hard momentum.

Analysis strategy

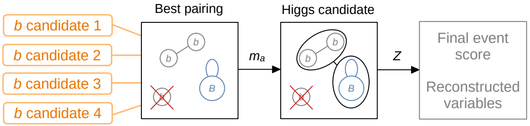


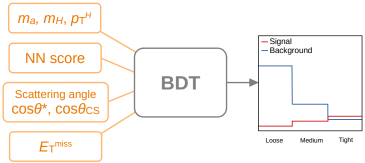
$H \to aa \to 4b$ and $H \to a_1 a_2 \to 4b$ (direct decay)

- Large fraction of the events can be fully reconstructed.
- Mass-parametrised NN to identify the best $a \to bb$ pairing hypothesis and define the signal regions.
- A BDT is trained in each signal region for the final signal vs. background discrimination.

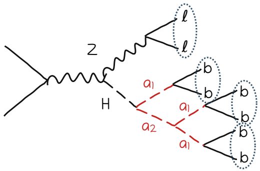
SR	B-jets	b-jets	SVs	NN score	BDT score
2B	2	0	0	> 0.5	any
1B2b	1	2	0	> 0.05	any
1B1b1v	1	1	1	> 0.05	any
4b	0	4	0	> 0.05	any
3b1v	0	3	1	> 0.05	any

Control regions are defined either with NN score ≤ 0.05 (0.5 in 2B) or $\ell\ell = e\mu$





Analysis strategy

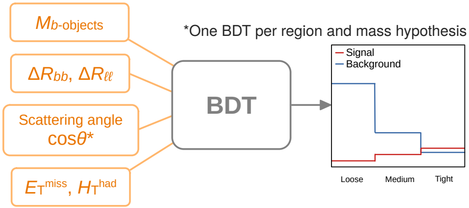


$H \to a_1 a_2 \to 6b$ (cascade decay)

- Very difficult to reconstruct the full event.
- No NN reconstruction is applied. Signal regions are defined by counting *b*-objects.
- A BDT is trained in each signal region for the final signal vs. background discrimination.

SR	*B*-jets	*b*-jets	SVs	BDT score
2B	≥2	=0	any	Medium,Tight
2B1b	≥2	≥1	any	Medium,Tight
1B2b	=1	≥2	any	Medium,Tight
4b	=0	≥4	=0	Medium,Tight
4b1v	=0	≥4	≥1	Medium,Tight
3b1v	=0	≥3	≥1	Medium,Tight

Control regions are defined either with BDT score = Loose or $\ell\ell = e\mu$



Analysis strategy

Asimov fit

- A binned likelihood fit is used to compute the **expected limit with a 95% CL**.
- This calculation depends on the **signal strength** and a set of **nuisance parameters** (background normalisation, systematic uncertainties...), as well as the analysis framework.
- The distribution of choice for this calculation is the **BDT score in each signal region**.
- At the same time, **control regions** are used to check background modelling.

Systematic uncertainties

- There are many sources of uncertainty to consider when performing an ATLAS analysis. Here are some of them:

Detector	**Leptons**	**Jets**	***b*-objects**	**Modelling**	...
Luminosity	Trigger	JVT	*b*-tagging	MC generator	
Pileup	Isolation	JER/JES	*B*-tagging	MC parton shower	
	ID	Composition	SV-tagging	PDF	
		Calibration		Background modelling	

Results

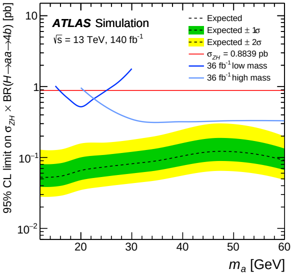
$H \to aa \to 4b$

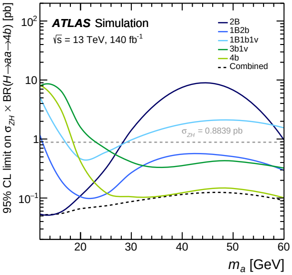
- There are two previous ATLAS studies at 36 fb^{-1} for this decay channel:

  - $m_a \in [15, 30]$ GeV [arXiv:2005.12236]
  - $m_a \in [20, 60]$ GeV [arXiv:1806.07355]

- This analysis covers the mass range $m_a \in [12, 60]$ GeV at 140 fb^{-1}.
- Improved sensitivity due to higher luminosity and improved b identification techniques.

Good sensitivity in the transition region (20-30 GeV)





The 2B region allows to explore m_a down to 12 GeV

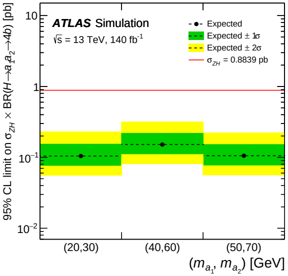
1B2b and 1B1b1v regions improve sensitivity in the mixed regime (~20 GeV)

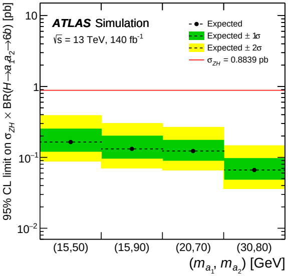
Results

$H \to a_1 a_2 \to 4b/6b$

- There are no previous studies on this decay channel.
- Direct decays: (m_{a_1}, m_{a_2}) = (20,30), (40,60), (50,70) GeV.
- Cascade decays: (m_{a_1}, m_{a_2}) = (15,50), (15,90), (20,70), (30,80) GeV.

Results in the same order of magnitude as $H \to aa$





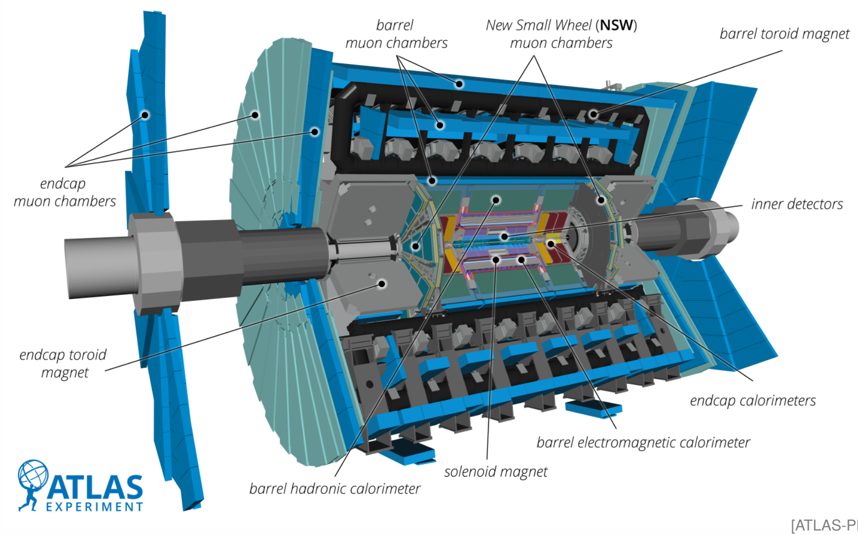
Similar sensitivity in $4b$ and $6b$ final states

Summary

- Two searches for **exotic Higgs decays** are presented, using the **full Run 2 dataset** of 140 fb^{-1} at $\sqrt{s} = 13$ TeV.
  - ▹ Improved results on $\text{BR}(H \to aa \to 4b)$.
  - ▹ First ever study of $H \to a_1 a_2 \to 4b/6b$ processes.
- **New *b*-tagging tools** developed for this analysis play a very important role $\Rightarrow$ **low-p_T *b*-tagging, *B*-jets, SVs**.
  - ▹ They will be used in other ongoing searches, such as $H \to aa \to 4b\ 0\ell$, $H \to aa \to bb\tau\tau$ and $tta,\ a \to bb$.
- The search for light spin-0 particles in ATLAS is not limited to the $a \to bb$ decay channel, with other existing studies including $a \to \tau\tau, \mu\mu, \gamma\gamma, gg$ and qq.

BACKUP

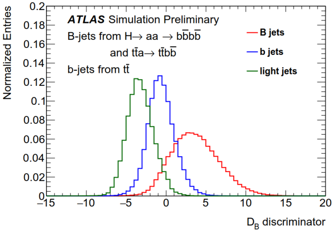
The ATLAS Detector

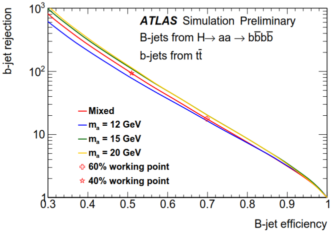


[ATLAS-PHOTO-2022-055]

DeXTer tagger for *B*-jets

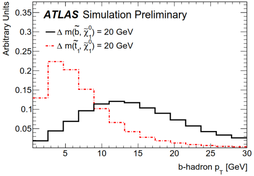
- Low-p_T $X \rightarrow bb$ tagger (20-200 GeV). Reference: ATL-PHYS-PUB-2022-042.
- Jets with $R = 0.8$ instead of the standard 0.4, which may not be sufficient to contain the full $X \rightarrow bb$ decay.

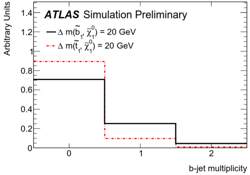


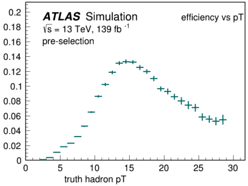


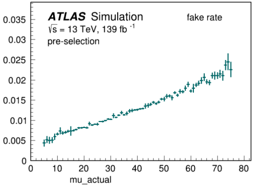
TC-LVT tagger for soft secondary vertices

- Soft *b*-hadron tagger (<15 GeV). Reference: ATLAS-CONF-2019-027.
- Used when the p_T is too low to produce a calorimeter jet.

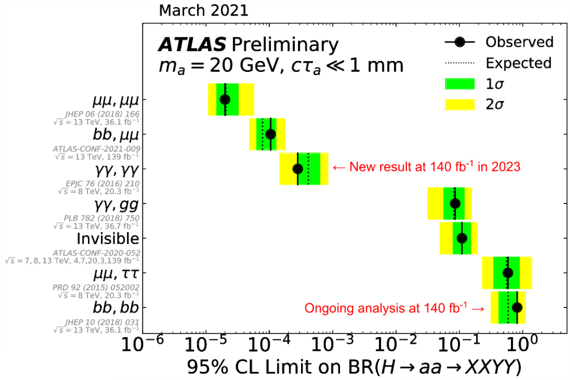






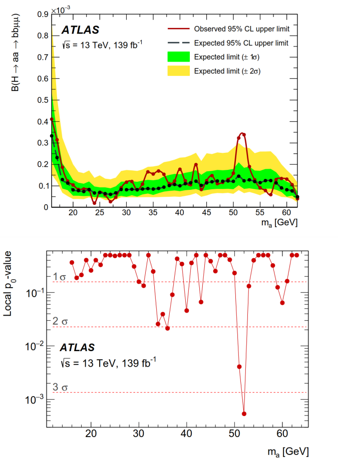


Summary plot from similar ATLAS analyses (Run 1 and 2)



Public results from similar ATLAS analyses at 140 fb^{-1}

H* → *aa* → *bbμμ [arXiv:2110.00313]



H* → *aa* → 4*γ [ATLAS-CONF-2023-040]