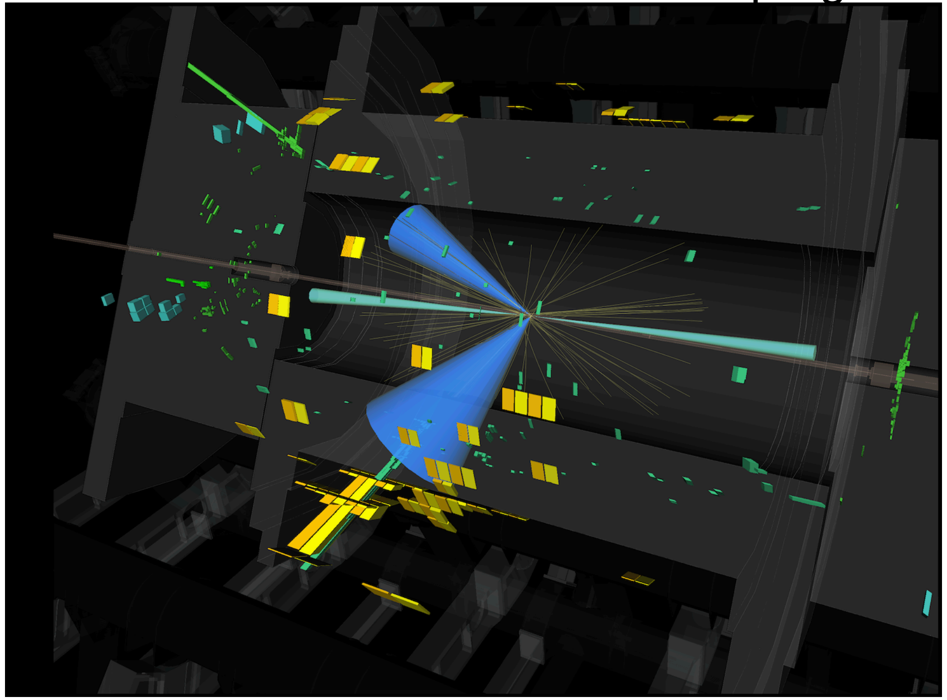
Search for VBF production of HH → 4b in the boosted regime using data collected by the ATLAS detector at $\sqrt{s} = 13$ TeV

ATLAS Work in progress



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06 March 2023

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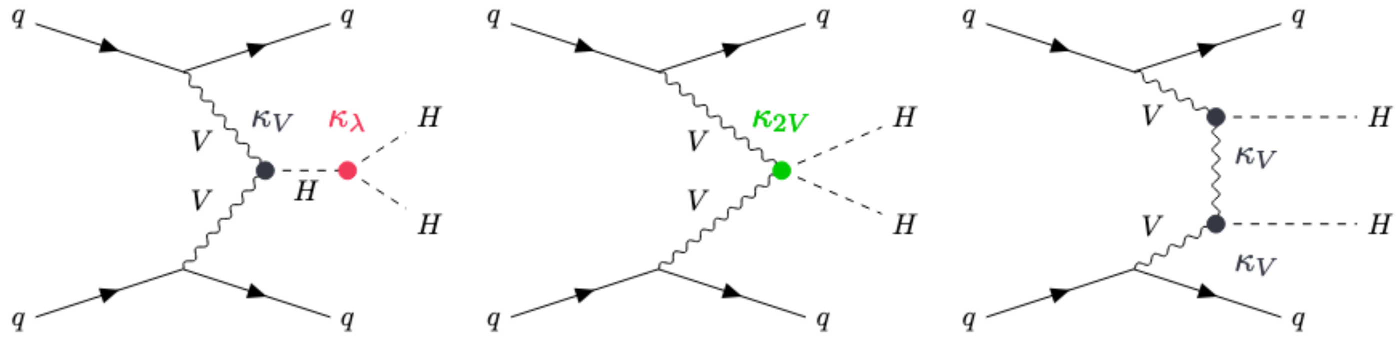
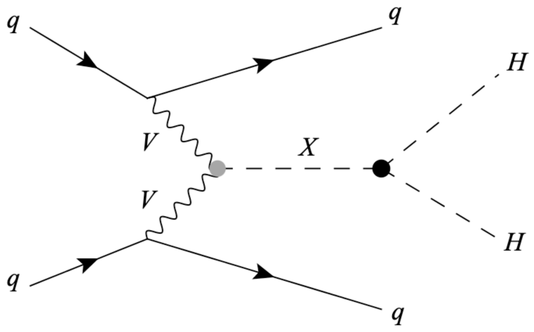
DESY.

Introduction & Motivation

- Better understanding of the Higgs mechanism is one of the top priorities in the LHC programme.
- Higgs boson pair production provides probe of both SM and BSM physics.
- Production via Vector-Boson-Fusion (VBF):
  - Sub-dominant production mode (1.726 fb at 13 TeV, m_H = 125 GeV)   [*dominant ggF with 31.05 fb*]
  - Unique access to the 2-Higgs-2-Bosons coupling.
  - BSM models for resonant production. [2HDMs, Composite Higgs model, etc.]



non-resonant production



resonant production

$$\left[\kappa_{2V} \equiv \frac{\lambda_{2V,BSM}}{\lambda_{2V,SM}}\right]$$

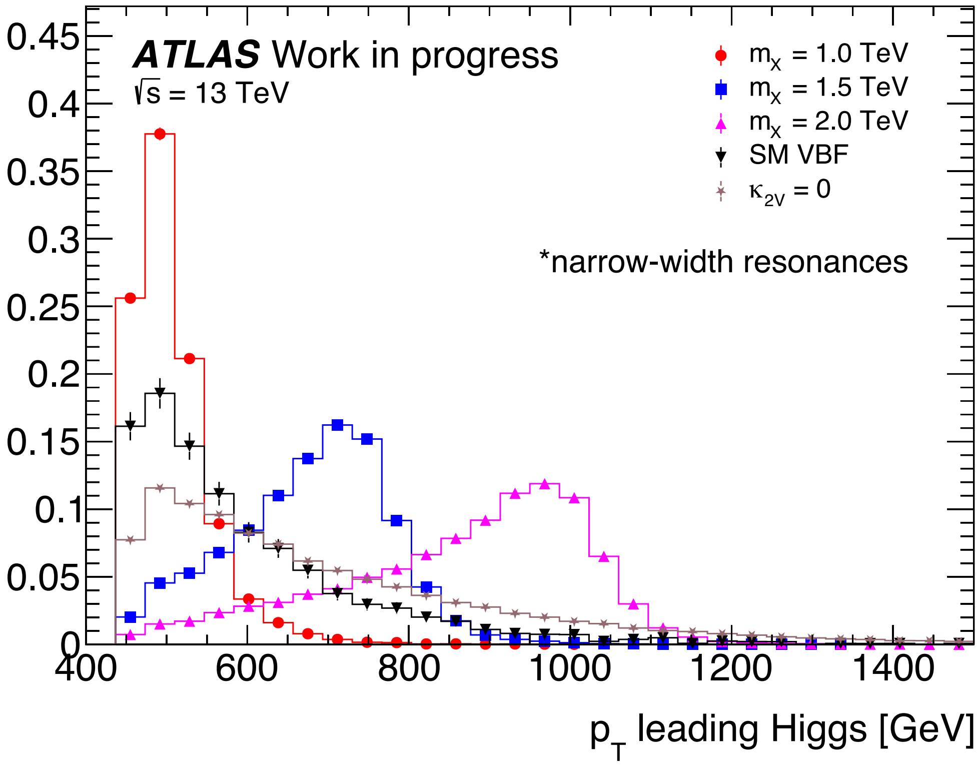
The decay to 4b-quarks

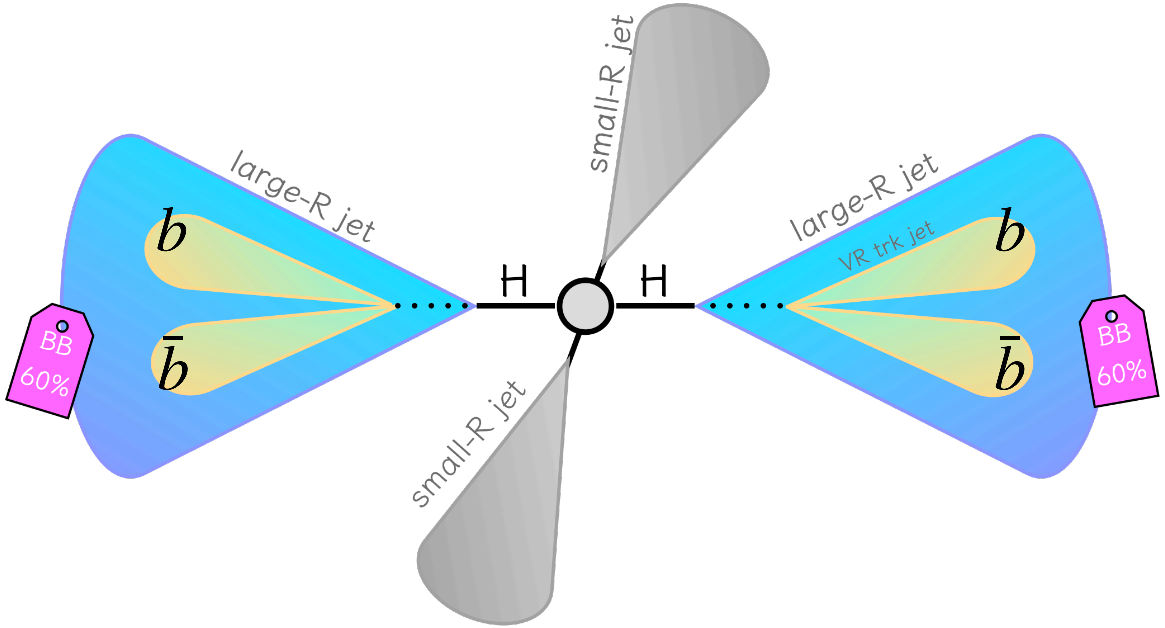
- Higgs pair decaying in 4 bottom quarks: largest branching ratio (~34%).
  - Advantages: large signal cross-section.
  - Difficulties: background enriched by QCD multi-jets and $t\bar{t}$ decay. [Hard to be modelled with simulation.]

	$b\bar{b}$	WW^*	gg	$\tau^+\tau^-$	$c\bar{c}$	ZZ^*	$\gamma\gamma$
$b\bar{b}$	33.9%	24.9%	9.5%	7.3%	3.4%	3.1%	0.3%
WW^*		4.6%	3.5%	2.7%	1.2%	1.1%	< 0.1%
gg			0.7%	1.0%	0.5%	0.4%	< 0.1%
$\tau^+\tau^-$				0.4%	0.4%	0.3%	< 0.1%
$c\bar{c}$					< 0.1%	0.2%	< 0.1%
ZZ^*						< 0.1%	< 0.1%
$\gamma\gamma$							< 0.1%

The boosted regime with 4b-quarks

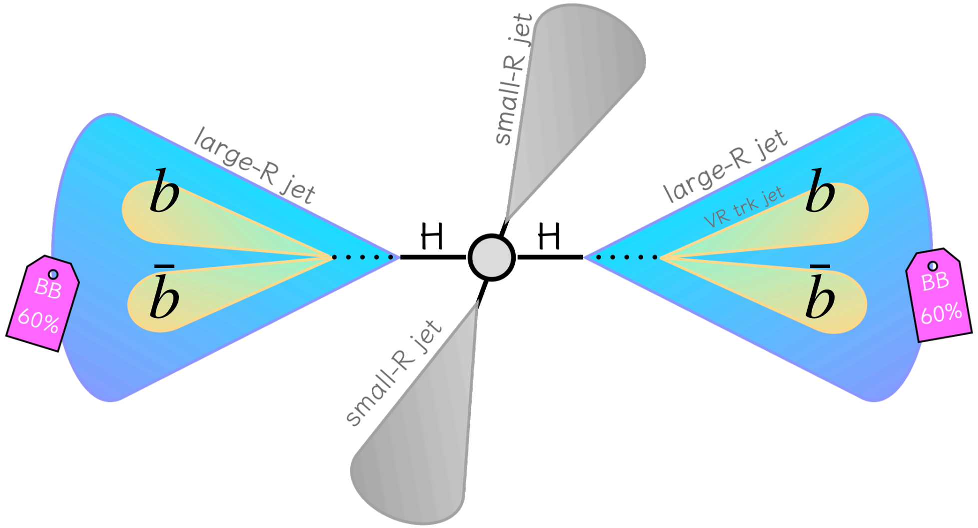
- Deviations in κ_{2V} from the SM ($\kappa_{2V} \neq 1$) or BSM resonant production: harder kinematics.
- Boosted regime: $b\bar{b}$ pairs from Higgs decays are reconstructed as *single large-radius jets*.
  - *Set constraints on κ_{2V} and upper limits on the cross-section for high-mass resonant models.*

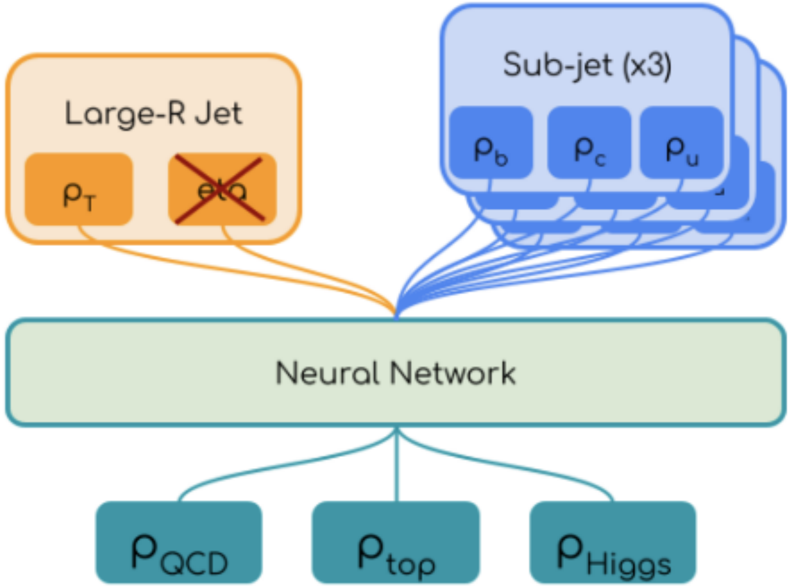




Event reconstruction

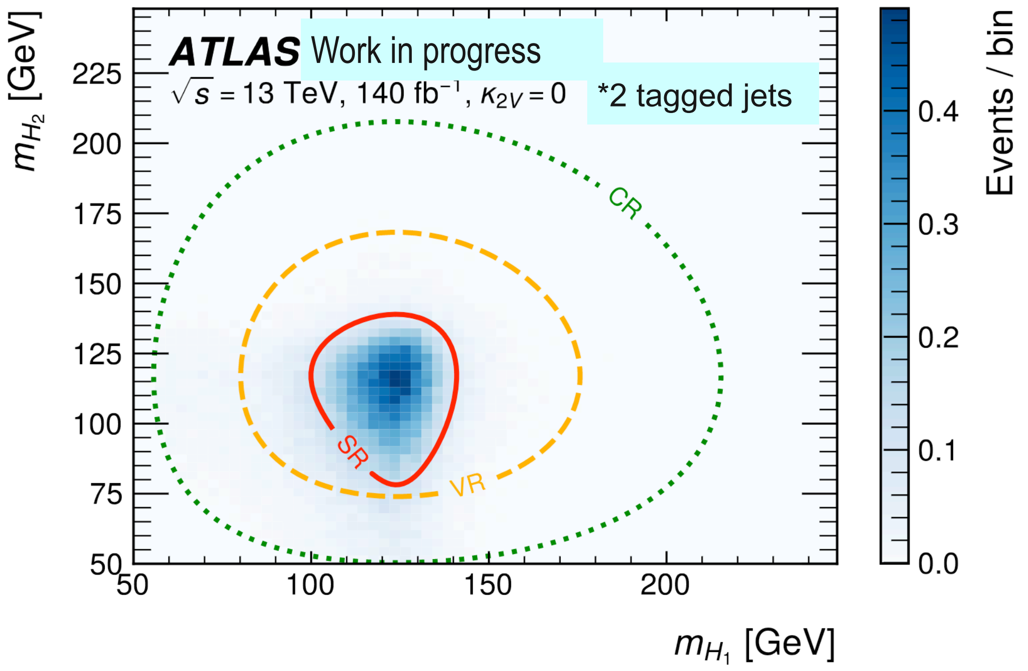
- 2 large-R jets (R=1.0) to fully capture the $H \rightarrow b\bar{b}$ decay.
- 2 small-R jets (R=0.4) for the two jets from the VBF signature.
  - [VBF jets typically in the region of $|\eta| > 2.5$]
- Double b-tagging algorithm to properly identify $H \rightarrow b\bar{b}$.
  - Reconstruct sub-jets candidates inside the Large-R jet.
  - Sub-jets are b-tagged using NN-based classifiers.
  - Large-R jet + sub-jets info in a NN to identify Higgs, QCD, or top decays.
  - Discriminator from the NN output.





Analysis Optimisation

- Set of cut-rules to maximise signal vs. background separation.
  - p_T and masses of the Higgs bosons;
  - Invariant mass and angular separation of the VBF jets;
- Signal-region defined using the mass-plane.
- Further discrimination power between
  Sig. and Bkg. in the SR using Boosted Decision Trees (BDT).



Background estimation

- QCD multi-jets difficult to model correctly.
- Employ data-driven estimate in SR using orthogonal X_{bb} criteria from control regions.

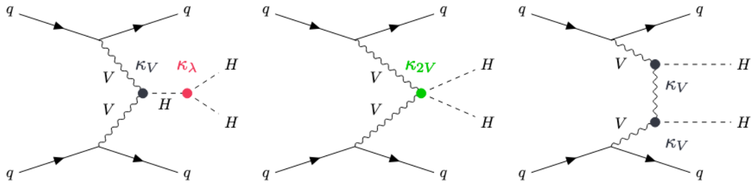
ATLAS Work in progress

	SR	VR	CR
Only 1 tagged H→bb	2649	6299	14921
2 tagged H→bb	Blinded	58	128

Apply Validate Learn

- Kinematics between different #tagged regions after applying event selection already very similar within statistical uncertainties.
  - Use shape from 1-tagged SR and apply normalisation factor derived from CR.
- Shape and normalisation systematic uncertainties derived using the VR.

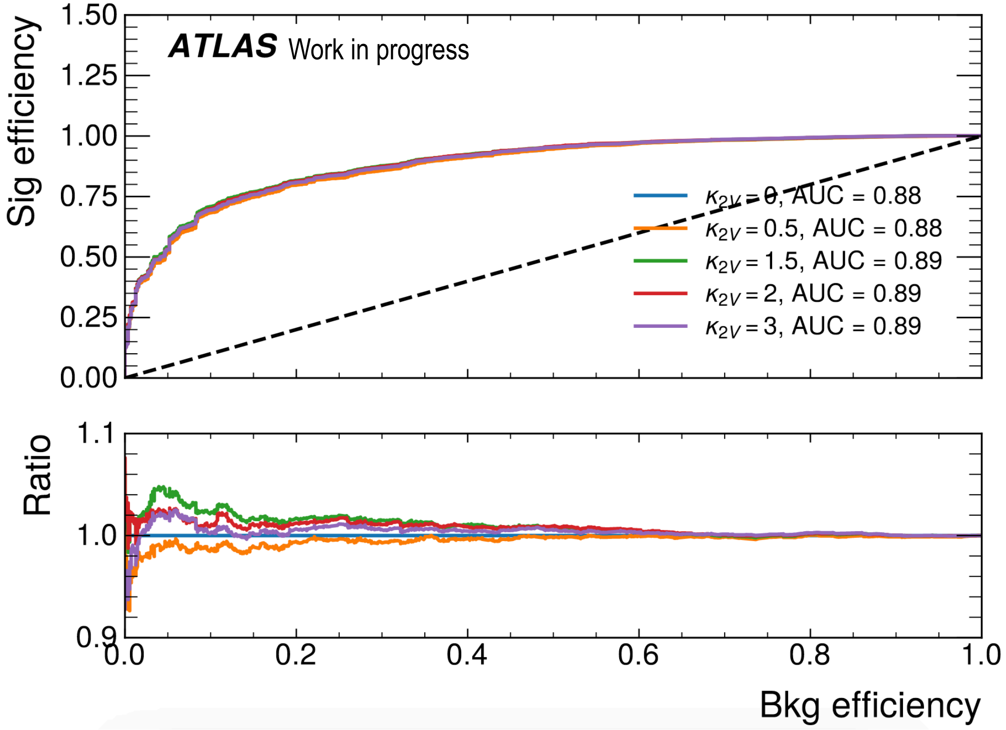
Non-resonant categorisation: BDT



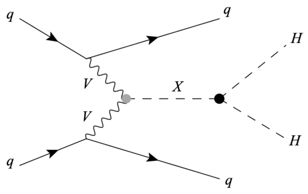
- Target of the non-resonant analysis: set constraints on κ_{2V}.
- BDT model trained using $\kappa_{2V} = 0$ signal sample and background to make discrimination.
- Input-features:

Relevant Objects	Kinematics used in training
Higgs Candidate (H_i, $i = 1, 2$)	$p_T^{H_i}$, η_{H_i}
Di-Higgs System (HH)	p_T^{HH}, η_{HH}, m_{HH}
VBF Jets (j_i, $i = 1, 2$)	$p_T^{j_i}$, η_{j_i}, E_{j_i}

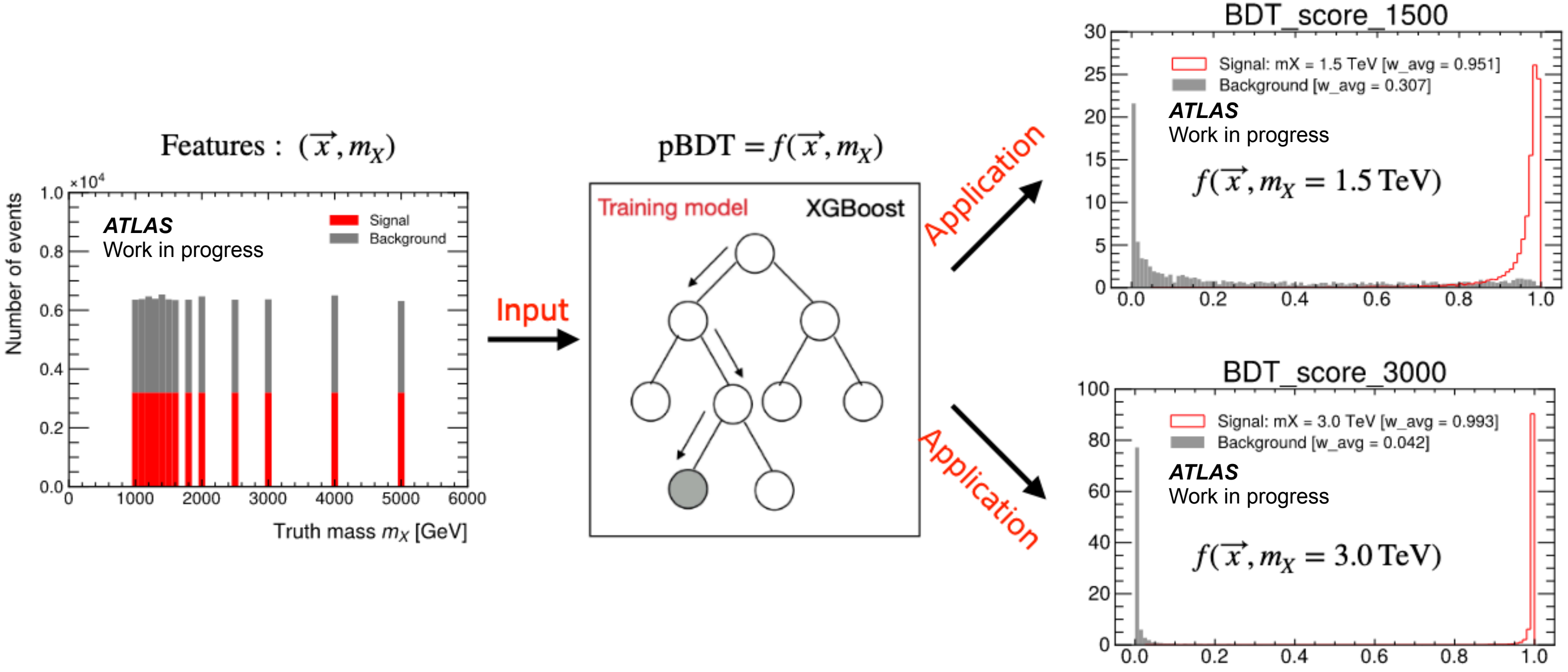
- Great response of the BDT model in discriminating background and other BSM signal samples with different κ_{2V}.

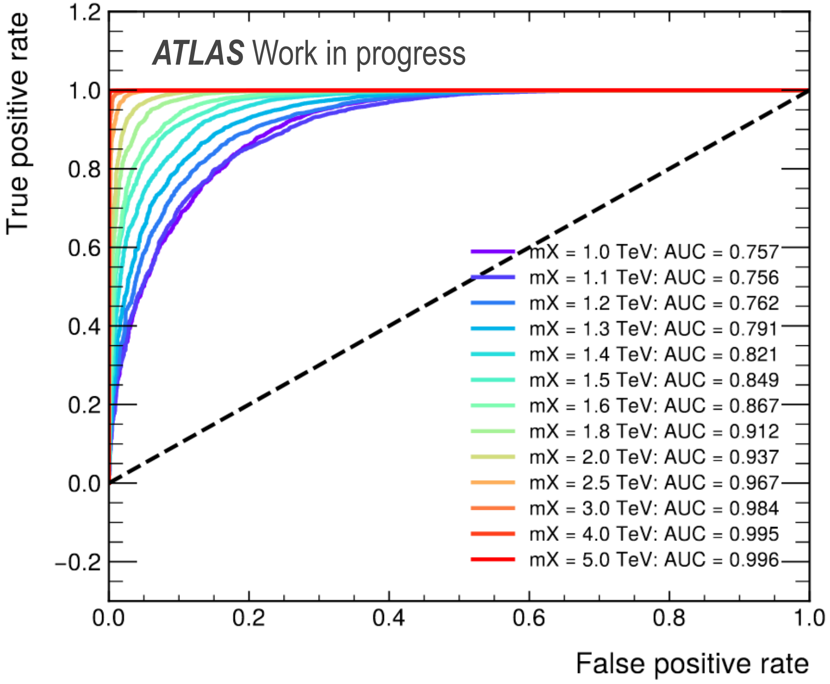


Resonant categorisation: parametric BDT (pBDT)



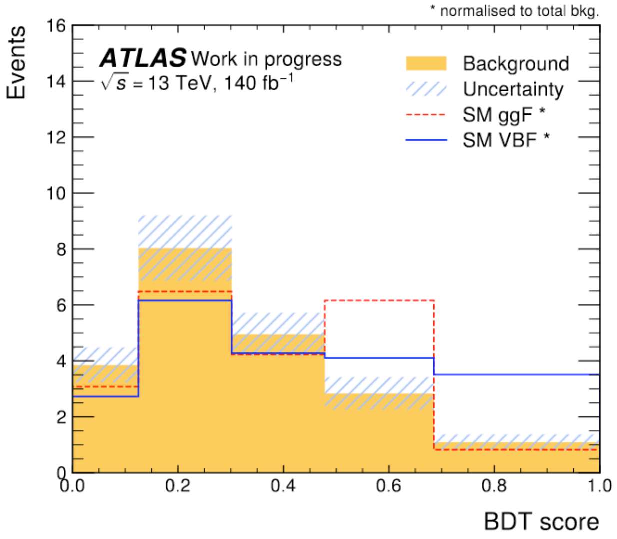
- Single BDT model capable to discriminate all mass point hypotheses (of our analysis) and background.
- Introduction of a parametric quantity in the input features.
  - Parametric variable: truth mass of the BSM resonant particle.
  - For background: no truth mass exists → random choices over the values available.
- If testing data against signal hypothesis of mass m_X → set truth mass to m_X.

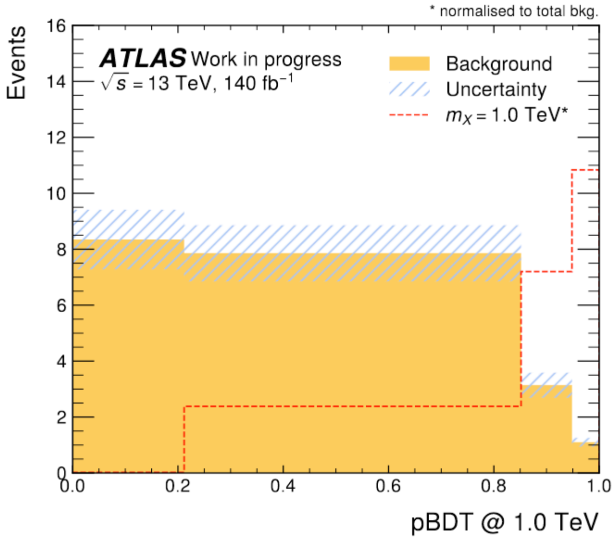




Statistical Interpretation

- Profile likelihood fits with expected bin content in histogram given by $\mu S + B$.
- Consider background-only hypothesis and set upper-limits in the cross-section.
- Use (p)BDT response distribution as fit variable.
- Statistical and systematic uncertainties included:
  - Analysis statistic limited (~70% of uncertainty)
  - X_{bb}-tagger (~30%), background estimation (~10%), and theoretical modelling (~7%) dominant systematic uncertainties.

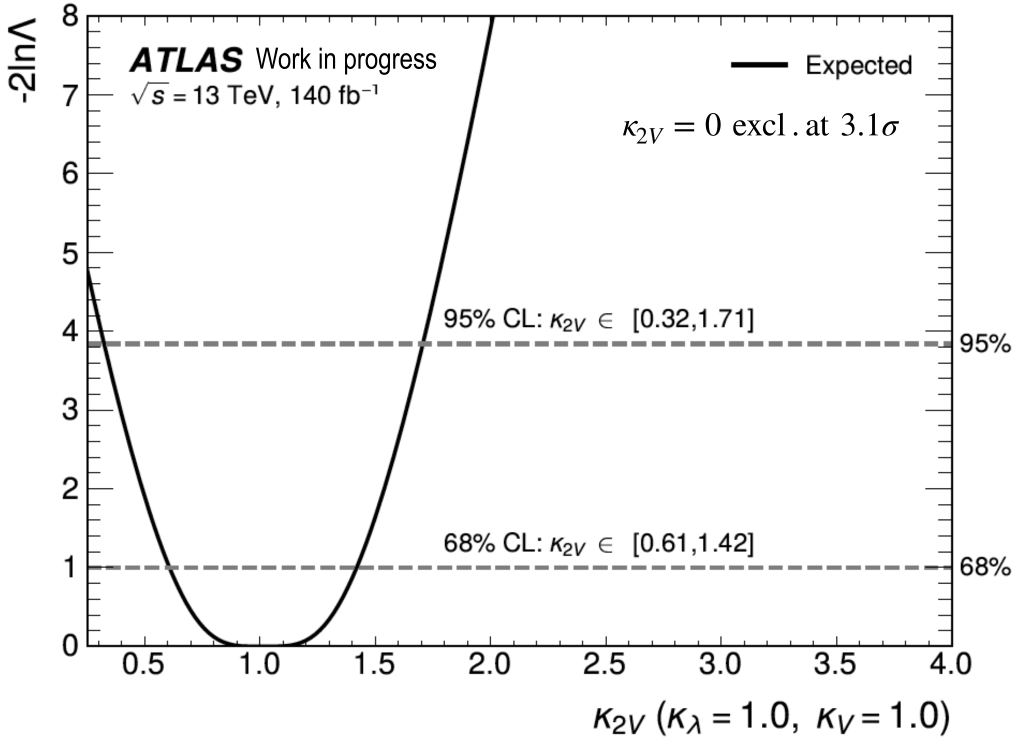


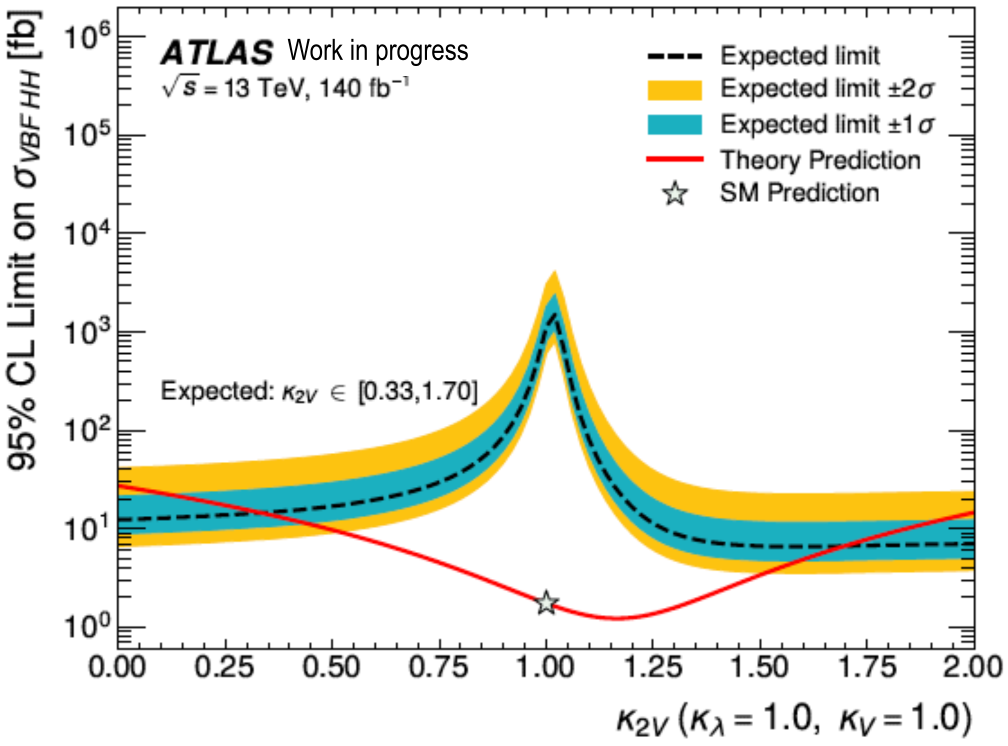


Non-resonant analysis: expected results

Boosted analysis only

- Vary values of κ_{2V} while keeping other Higgs couplings fixed to SM prediction.
- Constrain κ_{2V} from likelihood scan (CL_{s+b} method) or cross-section upper limit setting (CL_s method).

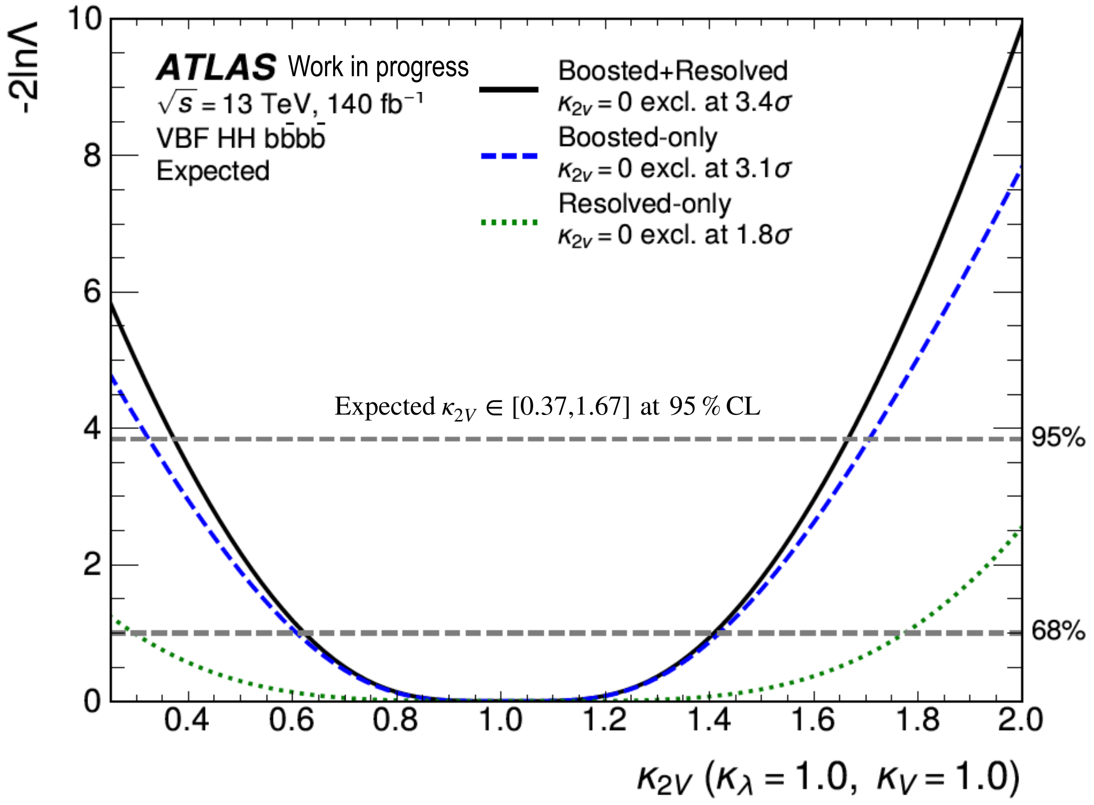


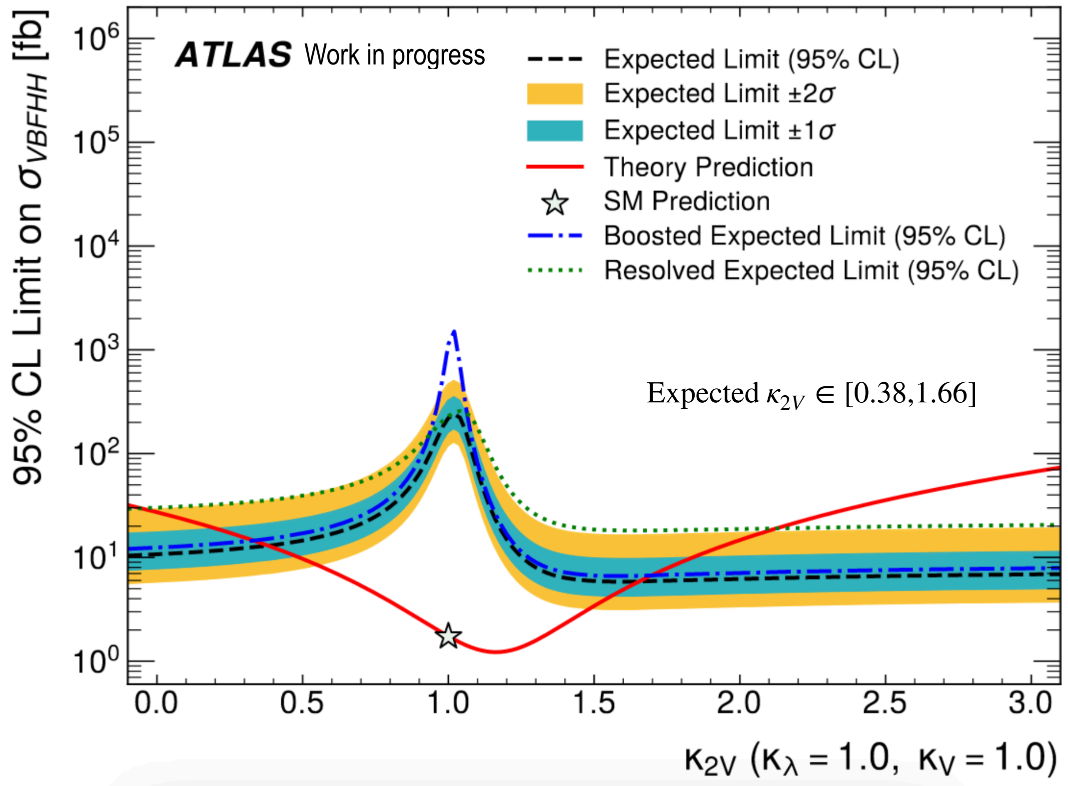


Non-resonant analysis: expected results

Combination with previous resolved analysis

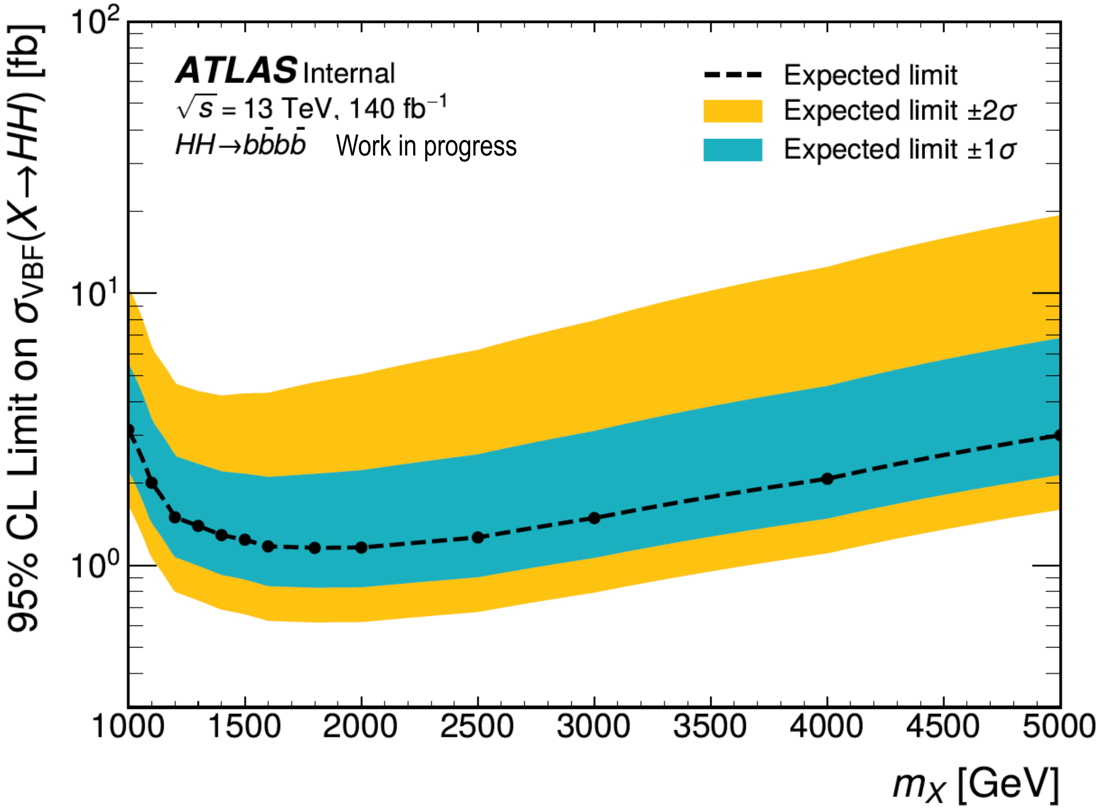
- Extra gain in sensitivity when combining results with previous *resolved* analysis [Phys. Rev. D 108, 052003].
  - Resolved analysis: each b-quark reconstructed individually as a small-R jet.
  - Full orthogonality between analyses: boosted-only analysis veto events inside the resolved SR.





Resonant analysis: expected results

- Set upper limits in the VBF $pp \to X \to HH$ cross-section as a function of m_X.
- Each mass hypothesis analysis uses the BDT with parametric input fixed to m_X.
- Expected results using samples under narrow-width hypothesis for X.



Conclusions

- Search for boosted VBF production of $HH \to b\bar{b}b\bar{b}$ to probe SM and BSM.
- Unique access to the 2-Higgs-2-Bosons coupling.
  - Expect to exclude $\kappa_{2V} = 0$ scenario with 3.4σ significance.
  - Expect to constrain κ_{2V} in the interval [0.38,1.66] at 95% CL.
- Resonant production of Higgs boson pairs via BSM resonant models can be tested.
  - Upper limits in the cross-section as a function of the BSM intermediate particle mass.

Thanks!

Questions?