SEARCHES FOR RESONANCES DECAYING TO PAIRS OF HIGGS BOSONS AT ATLAS

Kira Abeling for the ATLAS Collaboration

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ATLAS EXPERIMENT

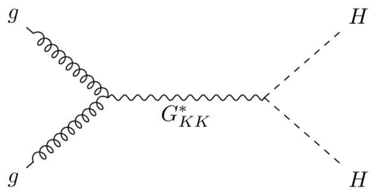
GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN IN PUBLICA COMMODA SEIT 1737

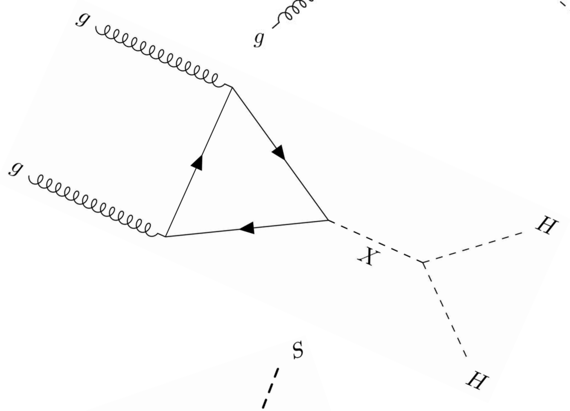
MOTIVATION

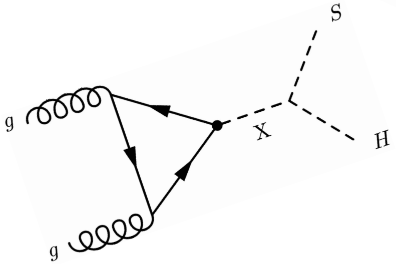
↪ because one Higgs boson simply isn't enough!

Higgs pairs – beyond the Standard Model

- New particles in many BSM theories
  - Try generic approach without much model dependence
  - spin-0 (generic scalar in narrow-width approximation)
  - spin-2 (Kaluza-Klein gravitons from bulk Randall-Sundrum model)
- X → HH example: Two-Higgs-Doublet-Model Phys.Rept. 516 (2012)
  - Introduce second Higgs doublet
  - Total of 5 “Higgs” bosons: *h*, *H*, *A*, H^+, H^-
  - Coupling H→ hh allowed, with h = discovered Higgs boson
- X → SH Example: two real singlet model Eur. Phys. J. C 80, 151 (2020)
  - Extend SM with two real scalar singlets
  - Total of 3 “Higgs” bosons: H, S, X
  - Masses of X and S not predicted: X→SH possible





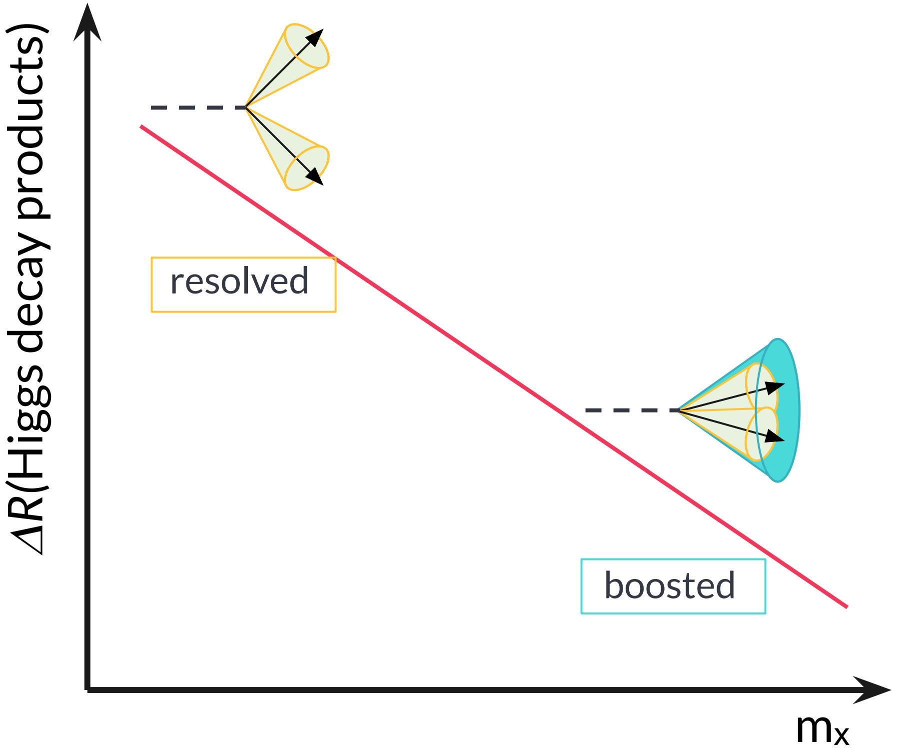


Higgs pair decays and topologies

- Higgs pair branching ratios

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

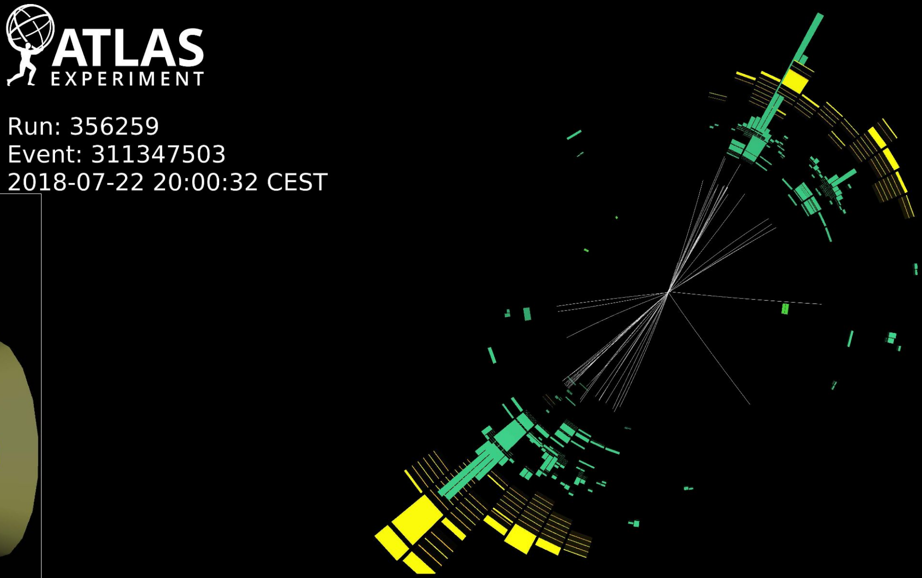
- high branching ratio vs clean signal
- Mass of resonance not predicted



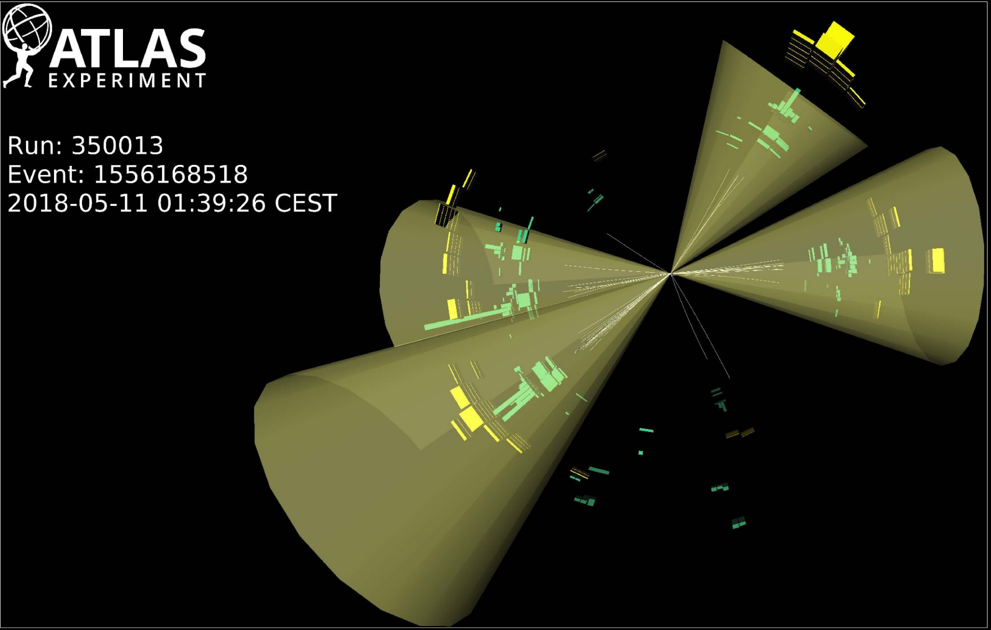
ggf → X → HH ANALYSES

↪ The “standard” searches

$X \to HH \to b\bar{b}b\bar{b}$ Phys. Rev. D 105, 092002 (2022)

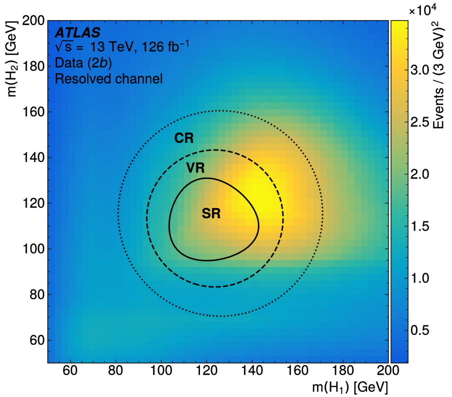


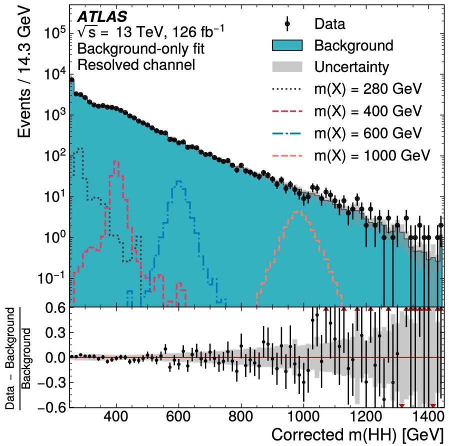
resolved



boosted

X→HH→$b\bar{b}b\bar{b}$ [Phys. Rev. D 105, 092002 (2022)]

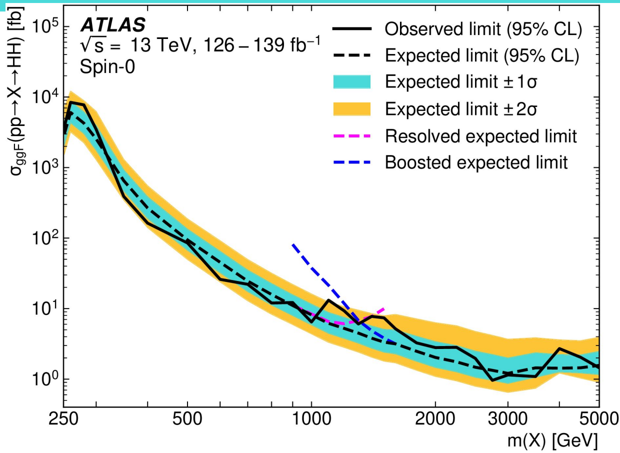


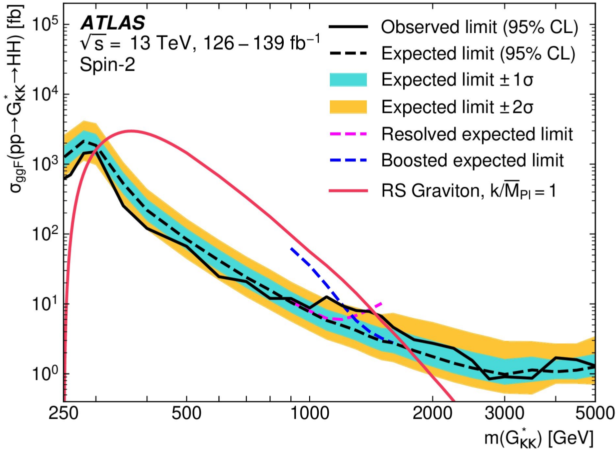


- Resolved analysis:
  - 4 b-tagged jets paired into 2 Higgs using a boosted decision tree
  - Extrapolate background from data in 2 b-tagged + 2 untagged jets region
- Boosted analysis:
  - 2 (single or double) b-tagged large-R jets
  - Extrapolate background from data in 1 (single or double) b-tagged large-R jet
- Signal region defined in $m(H_1)$-$m(H_2)$ plane

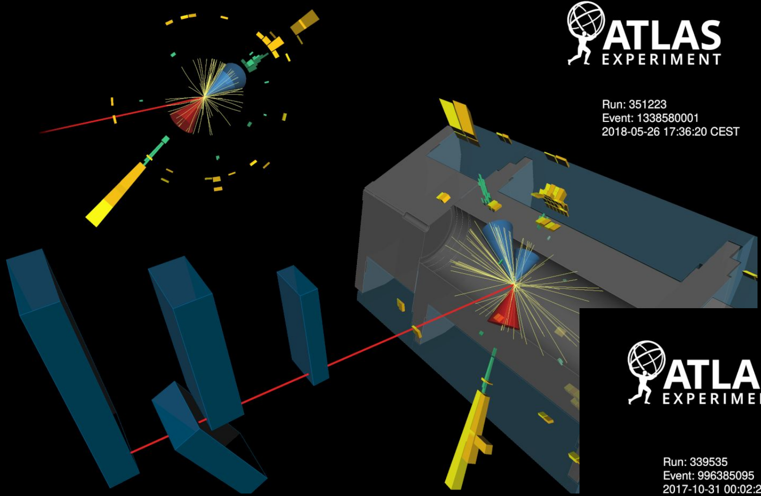
$$X_{HH} = \sqrt{\left(\frac{m(H_1) - 120\ \text{GeV}}{0.1 \times m(H_1)}\right)^2 + \left(\frac{m(H_2) - 110\ \text{GeV}}{0.1 \times m(H_2)}\right)^2}$$

  - Boosted: (124 GeV, 115 GeV)
- Limits on spin-0 as well as spin-2 resonance derived from m(HH) distribution

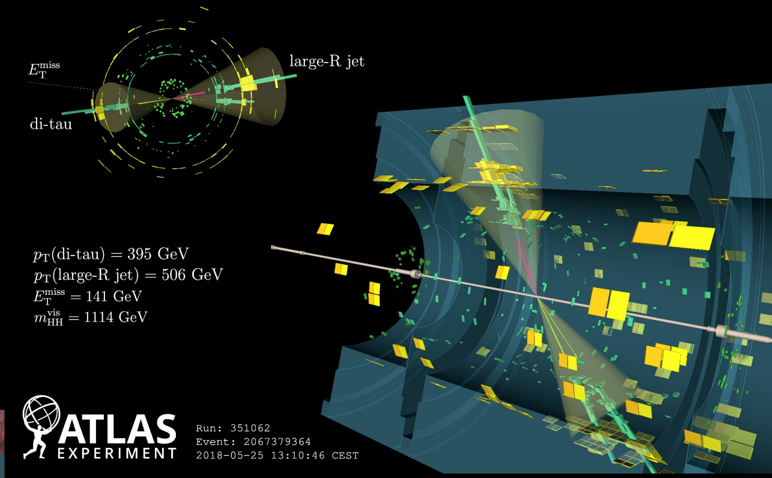


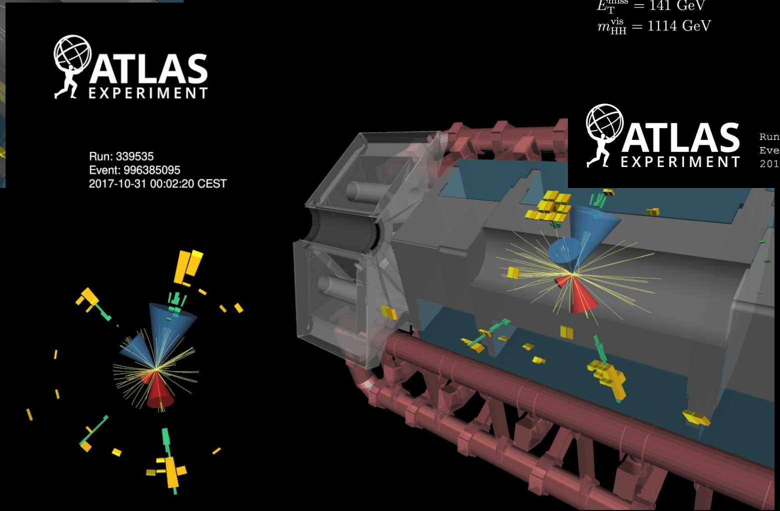


X→HH→$b\bar{b}\tau^-\tau^+$ JHEP 07, 040 (2023), JHEP 11, 163 (2020)



Resolved
had-had



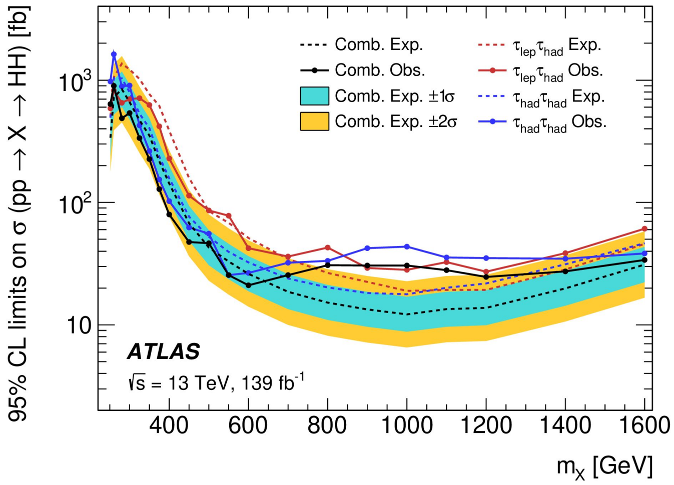


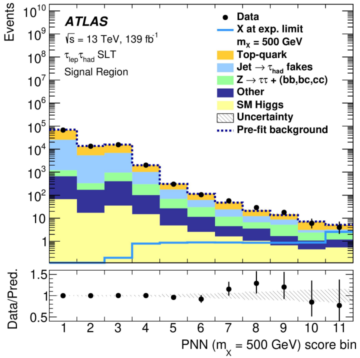
Resolved
lep-had

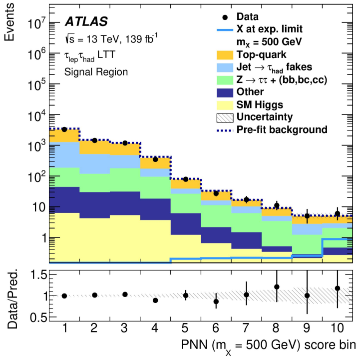
Boosted
had-had

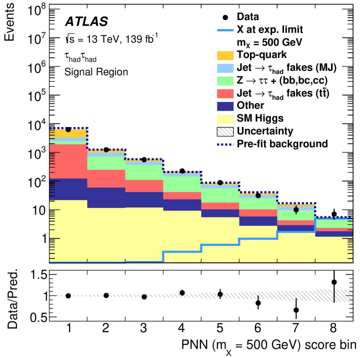
X→HH→$b\bar{b}\tau^-\tau^+$ (resolved) [JHEP 07, 040 (2023)]

- lep-had: 2 b-tagged jets, 1 electron/muon, 1 hadronic tau
  - Split into single-lepton and lepton + tau triggered events
- had-had: 2 b-tagged jets, 2 hadronic tau leptons
  - Use single tau and di-tau triggered events combined
- Backgrounds distinguished into real and fake tau contributions
  - Fakes are derived in a data driven approach
  - Z+heavy flavour cross section corrected in control region
- Parametrized neural networks trained to extract the signal



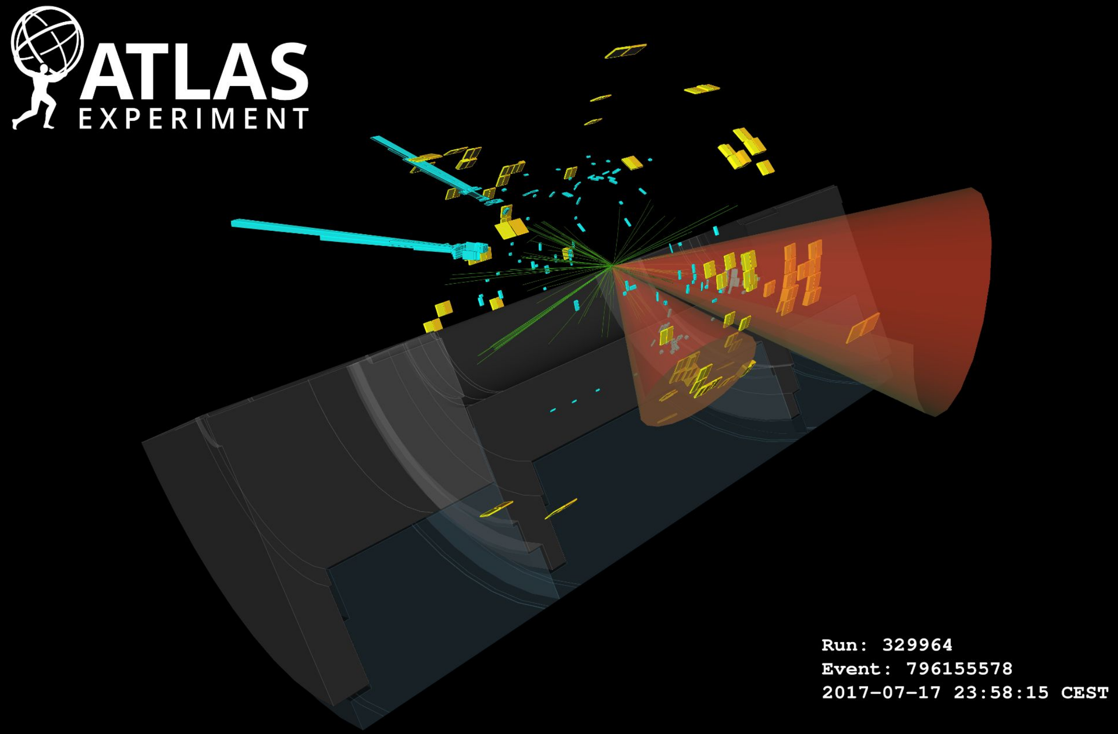






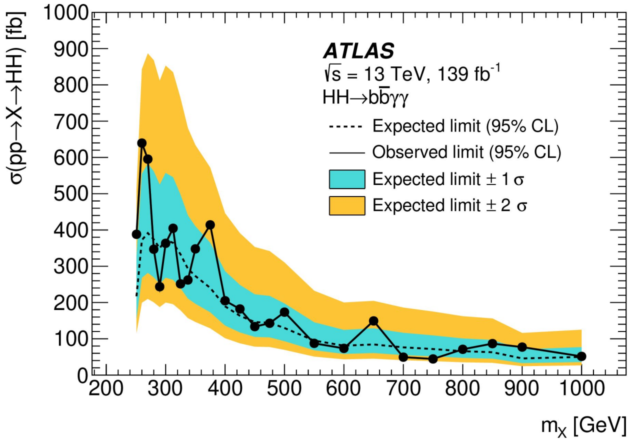
- Exclusion limits derived on PNN output distributions directly

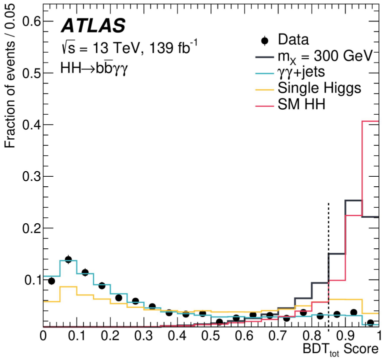
X→HH→$b\bar{b}\gamma\gamma$ Phys. Rev. D 106, 052001 (2022)

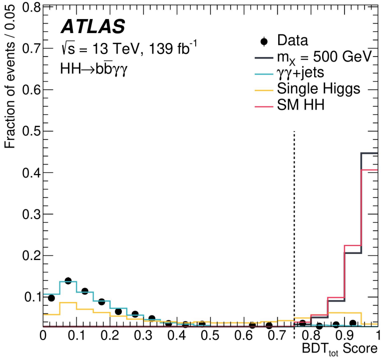


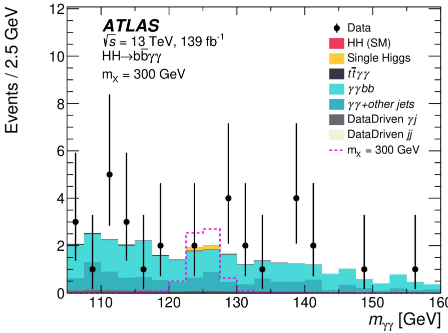
X→HH→$b\bar{b}\gamma\gamma$ [Phys. Rev. D 106, 052001 (2022)]

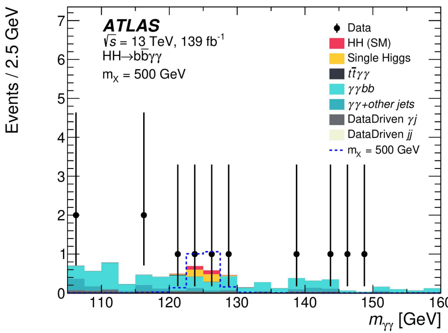
- 2 photons and 2 b-tagged jets with 105 GeV < m(γγ) < 160 GeV
- 2 boosted decision trees
  - separate signal against single Higgs or γγ background
  - signal = all mass points reweighted to match background m(bbγγ)
  - total BDT score linear combination of both BDT outputs
- Background determined from sideband fit using an exponential
- Exclusion limits obtained from fit of 120 GeV < m(γγ) <130 GeV









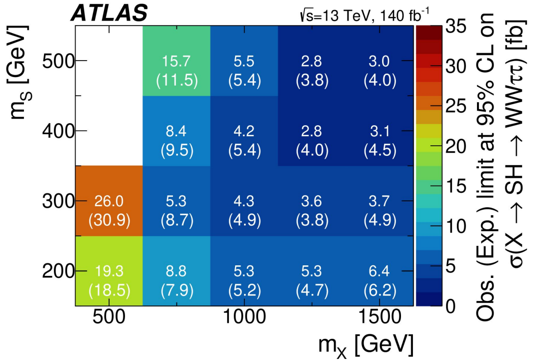


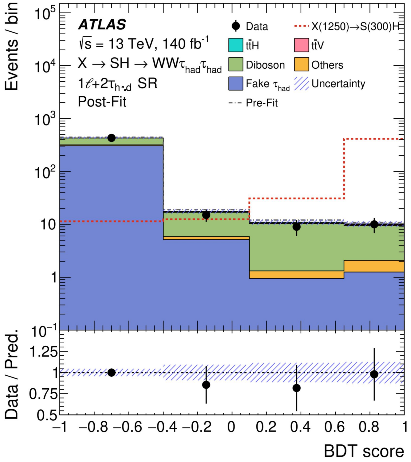
NON-“STANDARD” ANALYSES

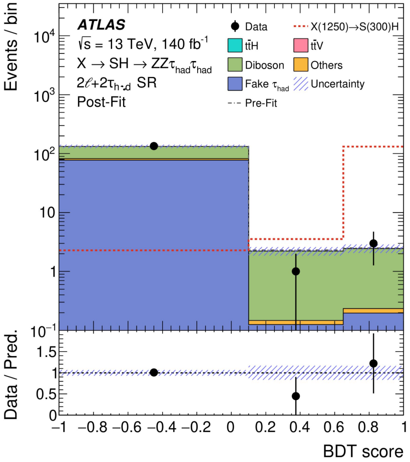
↪ Going one extra step

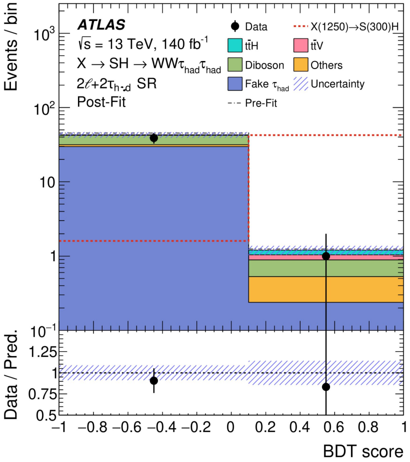
X→SH→VVτ⁻τ⁺ [arXiv:2307.11120 (2023)]

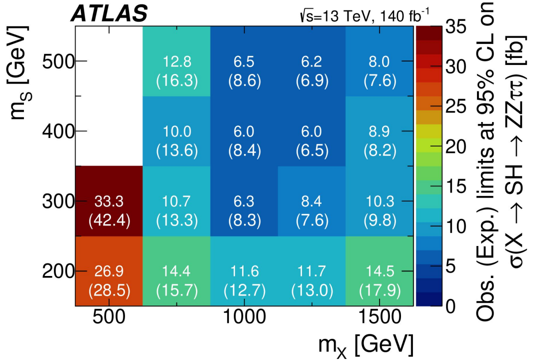
- Three signal regions ZZ2l2τ, WW2l2τ, WW1l2τ
  - Distinguished by number of light leptons and m(ll)
- Separate signal and background using boosted decision trees
  - split in signal regions and mass of S
  - m_X provided as a parameter, background gets assigned m_X randomly
- Exclusion fit performed on BDT output distributions





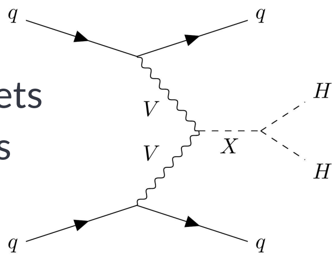


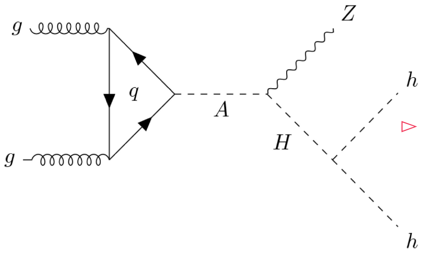


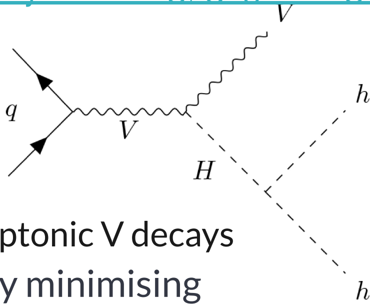


X→HH→b$\bar{b}$b$\bar{b}$ + extra

JHEP 07, 108 (2020) (Err. 2), Eur. Phys. J. C 83, 519 (2023)





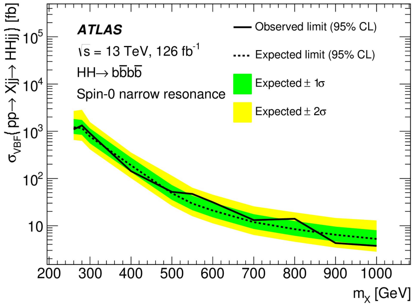


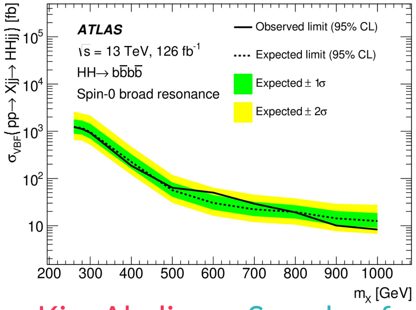
VBF

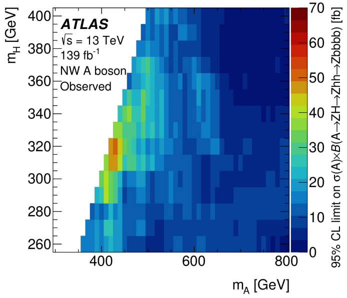
- 2 additional forward jets
- Combine b-tagged jets to Higgs based on kinematics and mass
- Follow X→HH→b$\bar{b}$b$\bar{b}$ analysis
  - region definitions
  - background estimate
  - m(HH) construction
  - Limit setting

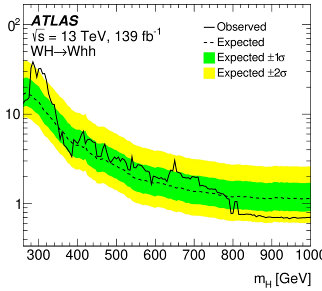
VHH

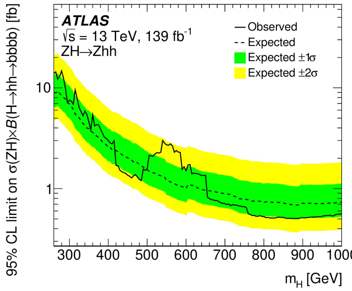
- 3 channels:
  - 0L, 1L, 2L
    Matching leptonic V decays
- 4 b-tagged jets paired to 2 Higgs by minimising $|m(H_1)-120\text{GeV}|+|m(H_2)-120\text{GeV})|$
- Train BDTs for all signal models in all channels
- Exclusion fit on BDT output distribution
  - Interpretation in the 2HDM model phase space











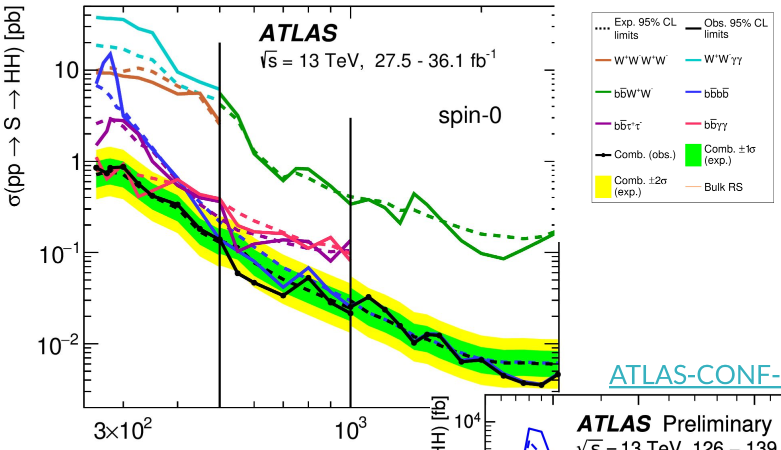
SUMMARY

↪ a glance in the past, present and future

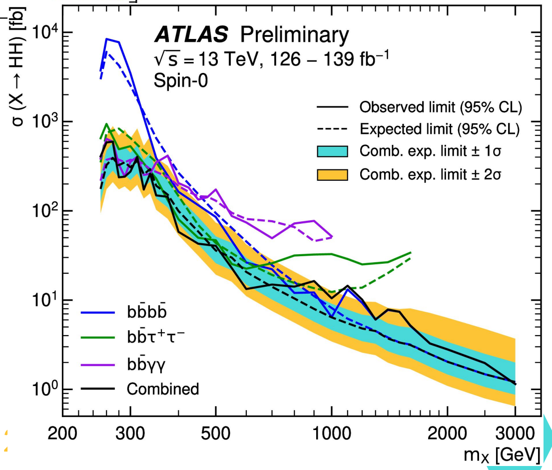
Summary – past, present, future

- Higgs boson pairs not observed so far
  - Many channels have been investigated including new decay and production channels!
  - Individual full Run 2 analyses better than combination of early Run 2
  - Small number of events limiting factor for most analysis
- More channels to be published soon including new decay channels and topologies
- Full Run-2 combination is ongoing
- Effort for Run 3 already started as well

Phys. Lett. B 800 135103 (2020)



ATLAS-CONF-2021-052



tHHank you for your attention

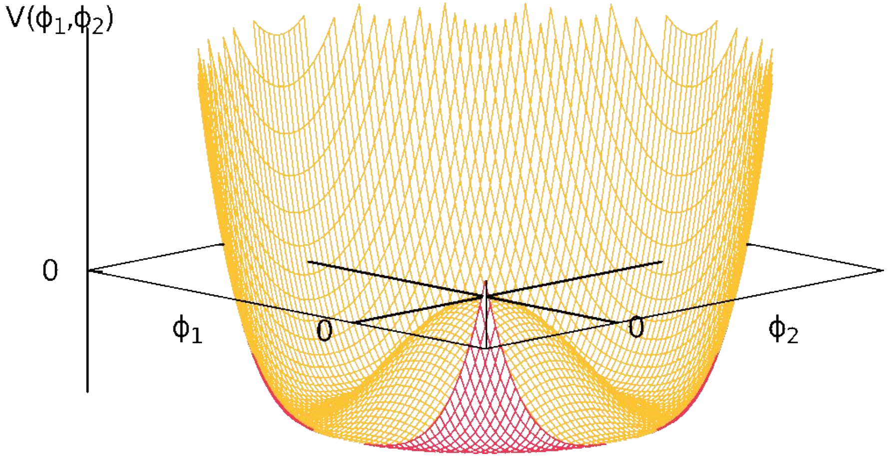
and stay curiouSH!

BACKUP

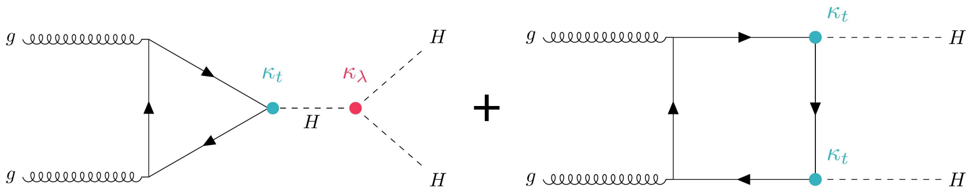
Higgs pairs – in the Standard Model

- Higgs scalar doublet $\Phi = \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$
- Potential: $V = \mu^2 \left(\Phi\Phi^\dagger\right) + \lambda \left(\Phi\Phi^\dagger\right)^2$

  with $\mu^2 < 0$ and $\lambda > 0$

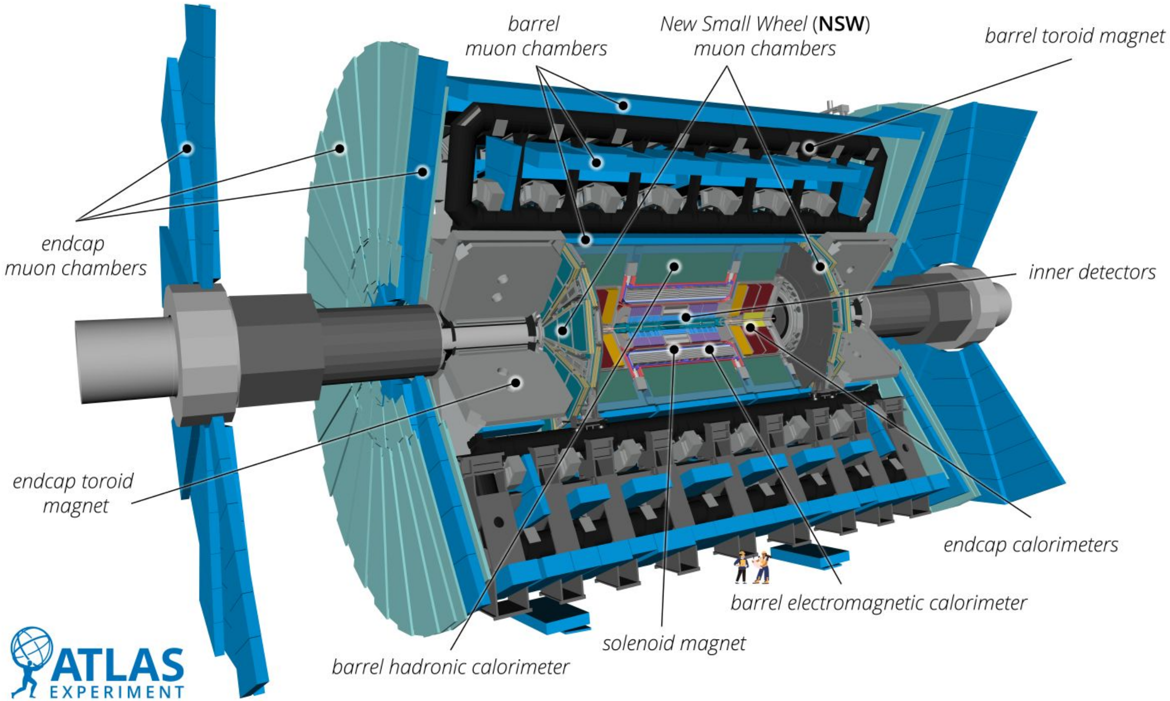


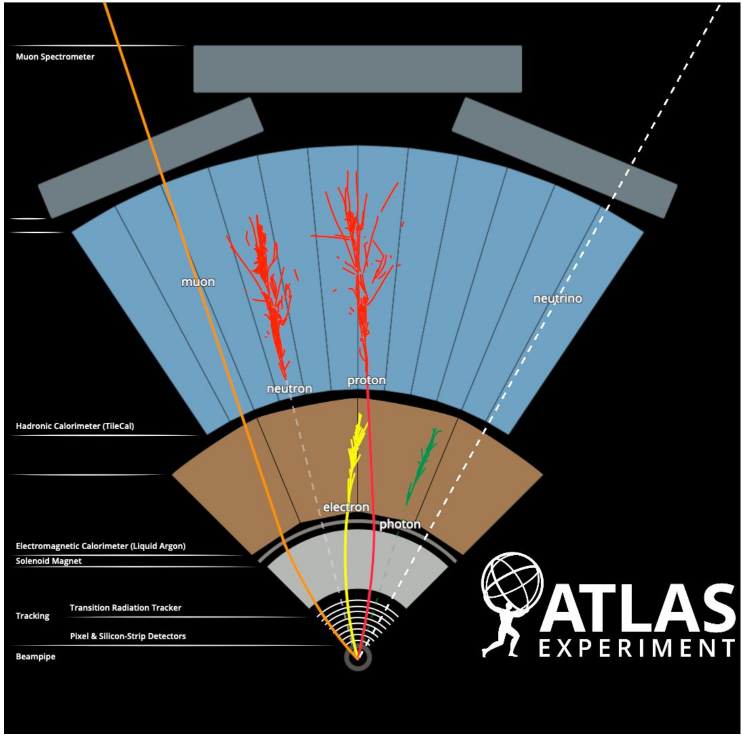
- Higgs pair production predicted by SM



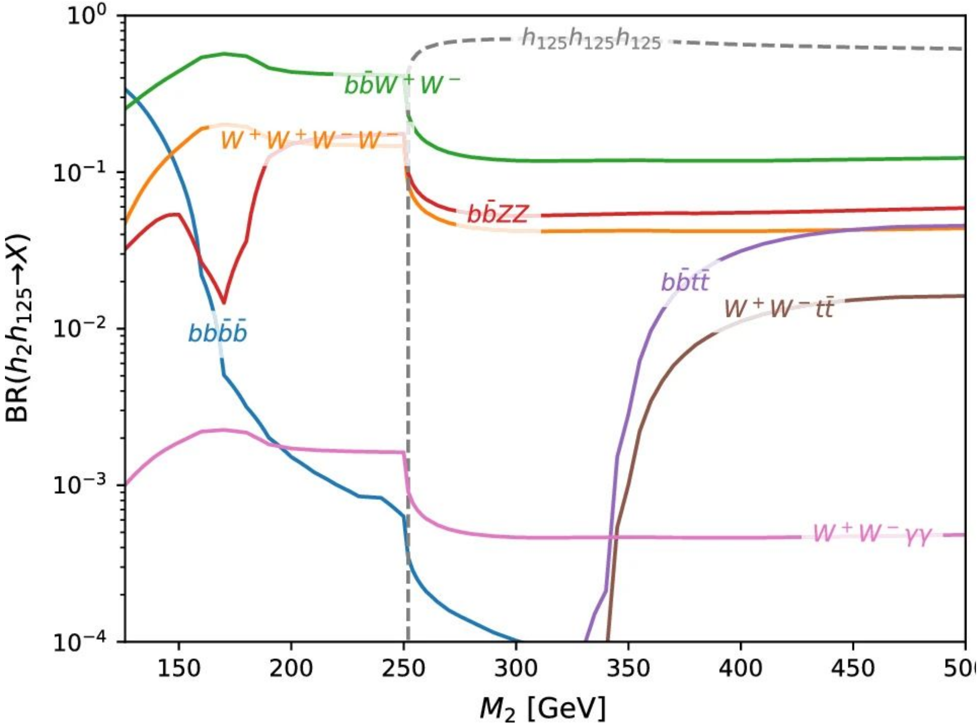
- destructive interference:
  - very low cross section (σ = 31 fb @ √s = 13 TeV)
- enhance through beyond SM mechanisms
  - coupling variation
  - new resonances

The ATLAS detector – and what it detects

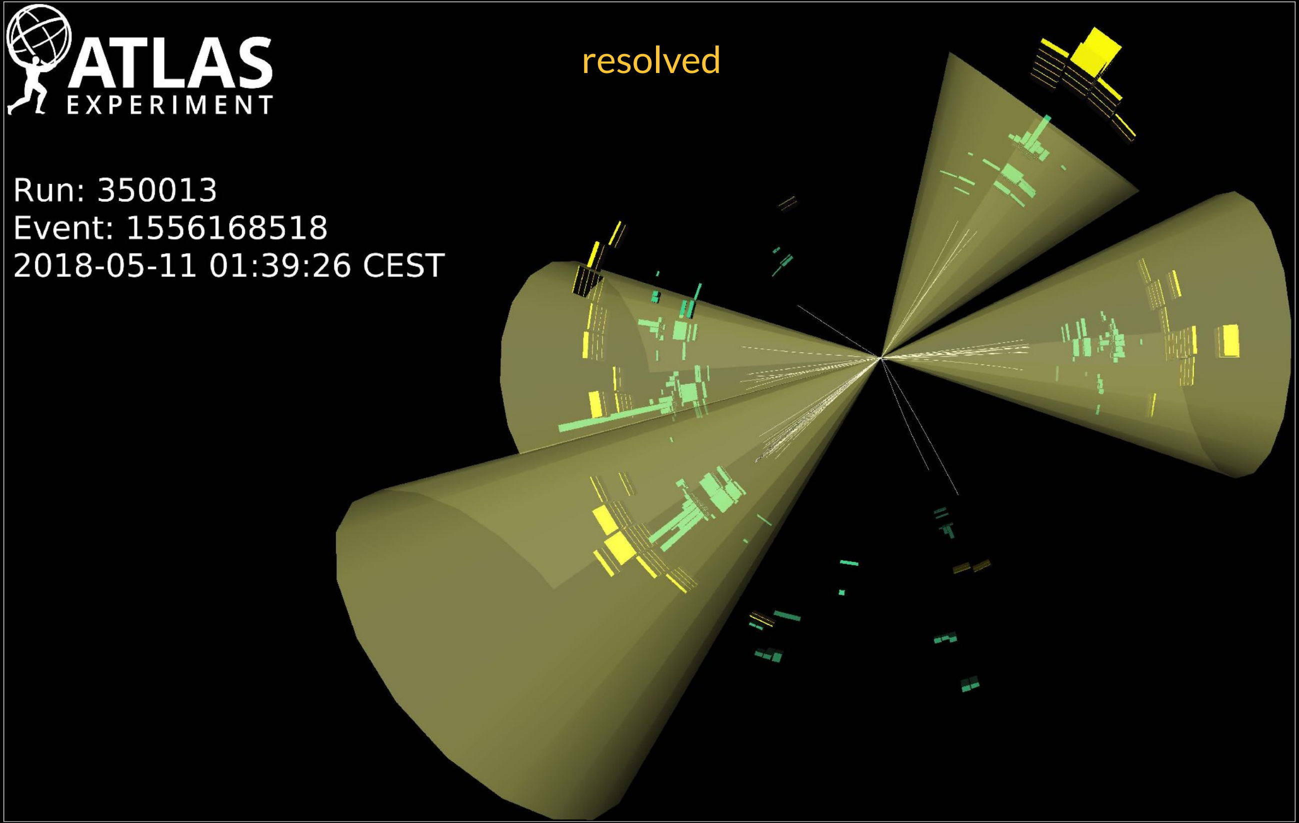




Higgs Pairs – BR(HS→SM) Eur. Phys. J. C 80, 151 (2020)



$X \to HH \to b\bar{b}b\bar{b}$ (resolved) [Phys. Rev. D 105, 092002 (2022)]



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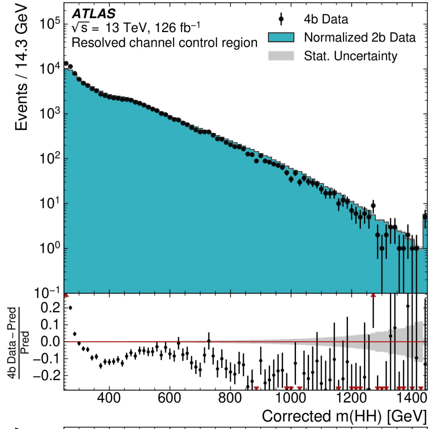
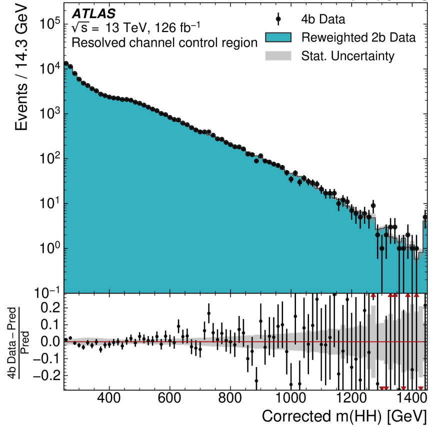
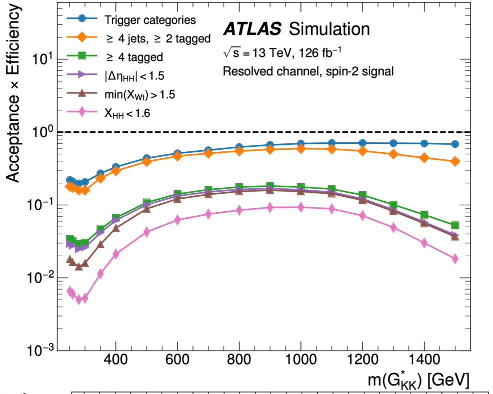
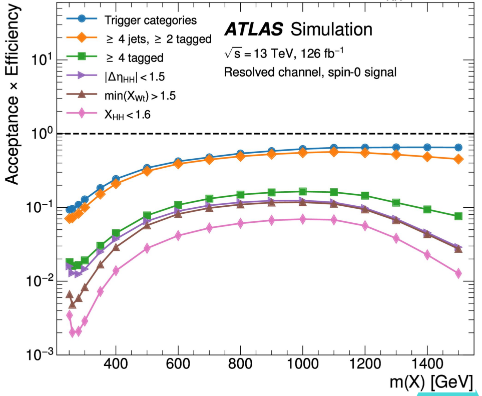




- To veto top events: $X_{Wt} = \sqrt{\left(\frac{m(W) - m_{\mathrm{SM}}(W)}{0.1 \times m(W)}\right)^2 + \left(\frac{m(t) - m_{\mathrm{SM}}(t)}{0.1 \times m(t)}\right)^2}$
- $R_{HH}^{\mathrm{VR}} \equiv \sqrt{(m(H_1) - 1.03 \times 120\ \mathrm{GeV})^2 + (m(H_2) - 1.03 \times 110\ \mathrm{GeV})^2} < 30\ \mathrm{GeV}$
- $R_{HH}^{\mathrm{CR}} \equiv \sqrt{(m(H_1) - 1.05 \times 120\ \mathrm{GeV})^2 + (m(H_2) - 1.05 \times 110\ \mathrm{GeV})^2} < 45\ \mathrm{GeV}$
- Background reweighting:
  - w(x)=p(4b,x)/p(2b,x) with p = PDF
  - p derived in 4b CR and applied to 2b SR
  - Optimal w derived by artificial NN trained on minimizing $\mathcal{L}(w(\vec{x})) = \int d\vec{x}[\sqrt{w(\vec{x})}p_{2b}(\vec{x}) + \frac{1}{\sqrt{w(\vec{x})}}p_{4b}(\vec{x})]$

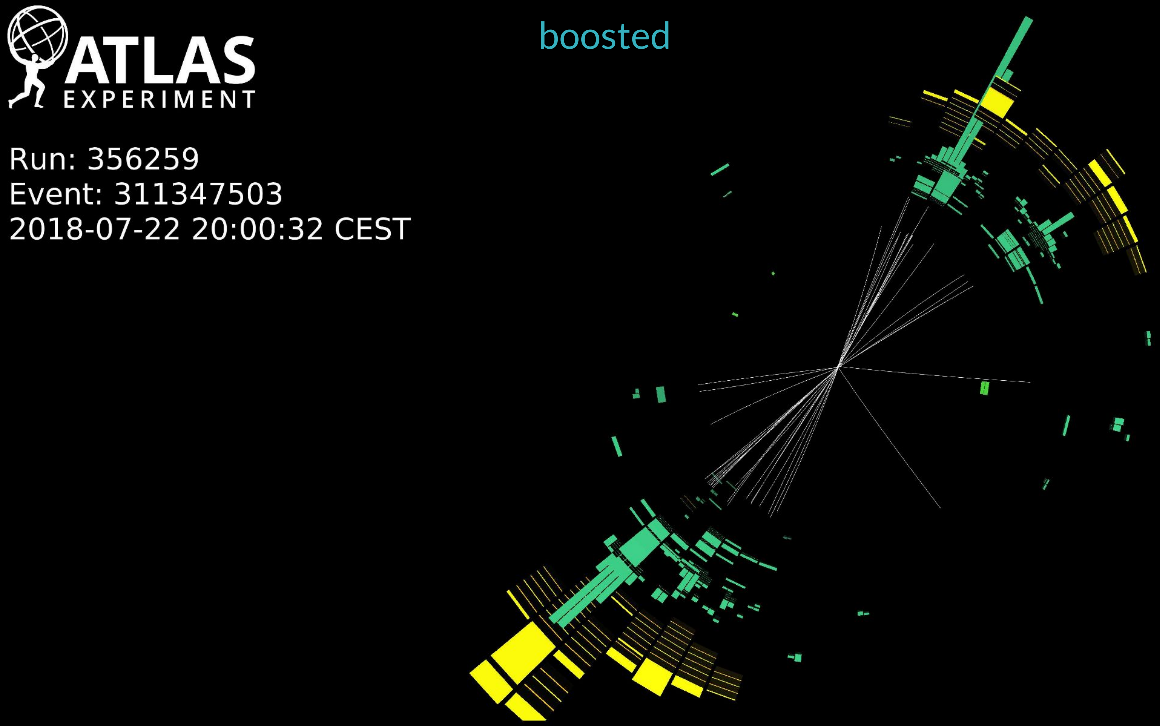
Uncertainty category	Relative impact [%]			
	280 GeV	600 GeV	1600 GeV	4000 GeV
Background $m(HH)$ shape	12.5	8.7	1.1	1.0
Jet momentum/mass scale	0.6	0.1	1.2	1.7
Jet momentum/mass resolution	2.1	1.5	7.1	7.8
b-tagging calibration	0.7	0.4	2.1	7.0
Theory (signal)	0.6	0.6	1.4	1.2
Theory ($t\bar{t}$ background)	N/A	N/A	0.5	0.2
All systematic uncertainties	15.9	10.9	13.4	15.6





X→HH→$b\bar{b}b\bar{b}$ (boosted) Phys. Rev. D 105, 092002 (2022)

boosted



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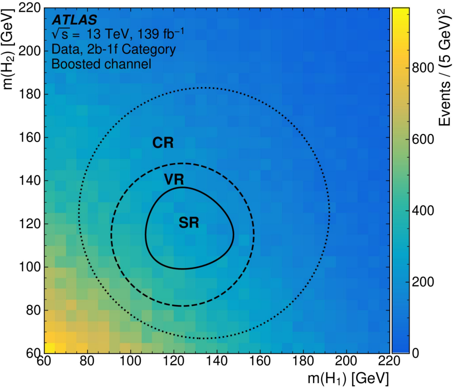
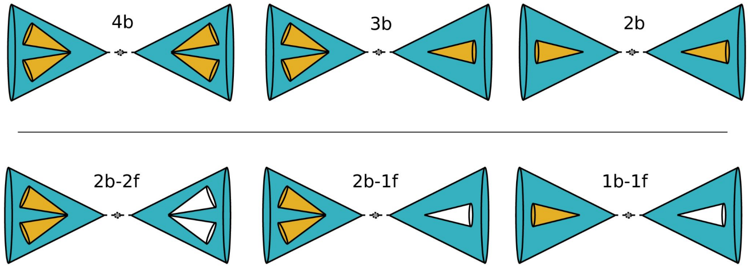
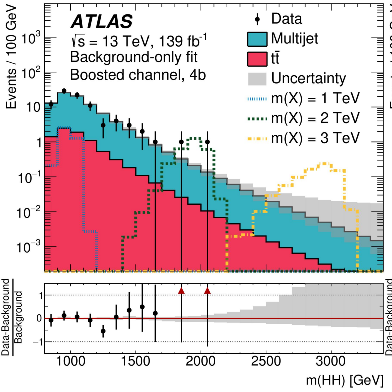
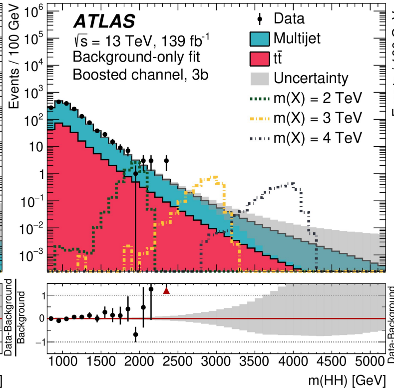
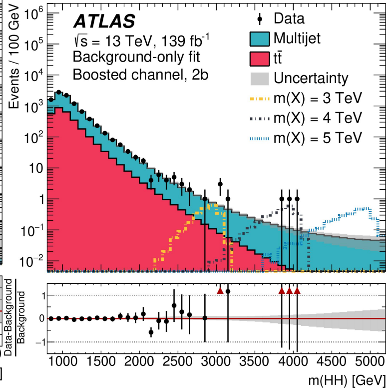


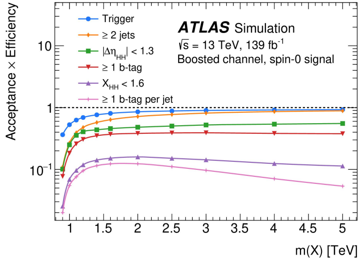
- Same procedure as resolved
- Background estimate in m(H₁)
  - $N^{\mathrm{hi}}_{i,\mathrm{data}} = \mu_{\mathrm{MJ}}^{n_b}\left(N^{\mathrm{lo}}_{i,\mathrm{data}} - N^{\mathrm{lo}}_{i,t\bar{t}}\right) + \alpha_{t\bar{t}}^{n_b} N^{\mathrm{hi}}_{i,t\bar{t}}$
  - μ and α estimated in maximum likelihood fit
  - Reweighted using cubic splines
    $w_i(\vec{x}) = w_{i-1}(\vec{x}) \times \left[\left(\prod_j f_{ij}(x_j) - 1\right) \times r_i + 1\right]$
  - Smoothed for m(HH)≥1200GeV

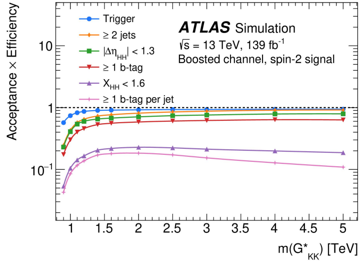


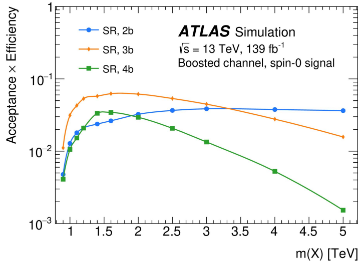


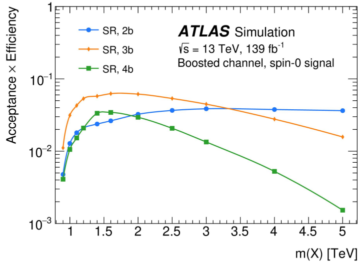




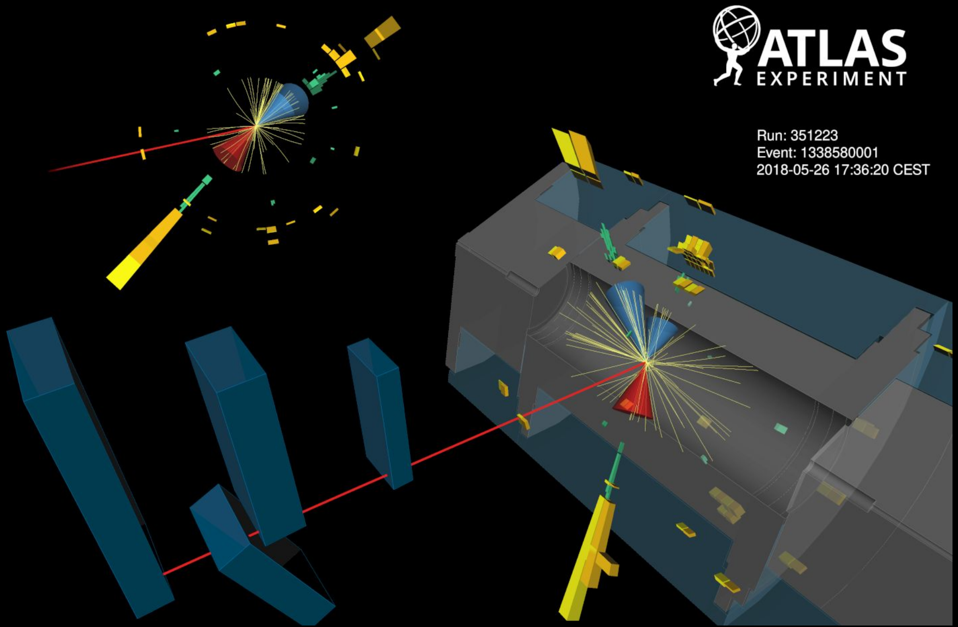




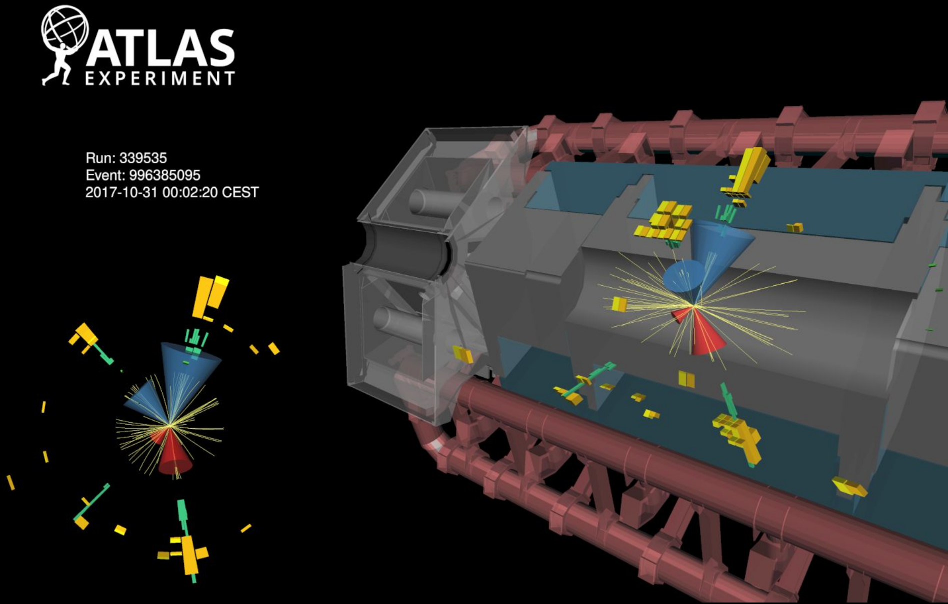




$X \to HH \to b\bar{b}\tau^-\tau^+$ (resolved) *JHEP 07, 040 (2023)*



Resolved lep-had



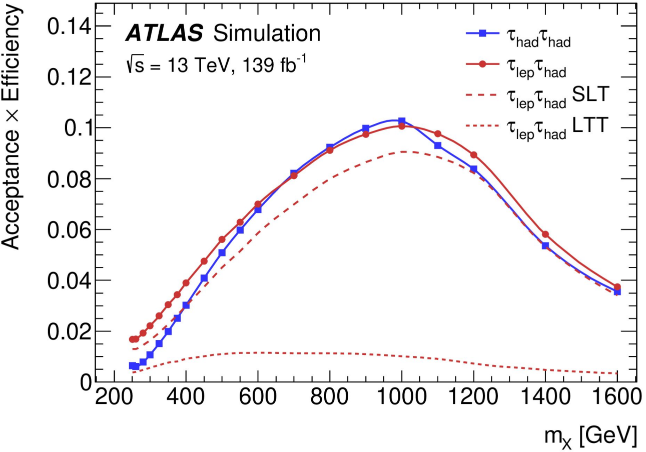
Resolved had-had

X→HH→$b\bar{b}\tau^{-}\tau^{+}$ (resolved) JHEP 07, 040 (2023)

$\tau_{\text{had}}\tau_{\text{had}}$ category		$\tau_{\text{lep}}\tau_{\text{had}}$ categories	
STT	DTT	SLT	LTT
e/μ selection			
No loose e/μ		Exactly one loose e/μ	
		e (μ) must be tight (medium and have $\lvert\eta\rvert < 2.5$)	
		$p_{\text{T}}^{e} > 25, 27$ GeV	18 GeV $< p_{\text{T}}^{e} <$ SLT cut
		$p_{\text{T}}^{\mu} > 21, 27$ GeV	15 GeV $< p_{\text{T}}^{\mu} <$ SLT cut
$\tau_{\text{had-vis}}$ selection			
Two loose $\tau_{\text{had-vis}}$		One loose $\tau_{\text{had-vis}}$	
		$\lvert\eta\rvert < 2.3$	
$p_{\text{T}} >$ 100, 140, 180 (25) GeV	$p_{\text{T}} >$ 40 (30) GeV		$p_{\text{T}} >$ 30 GeV
Jet selection			
≥ 2 jets with $\lvert\eta\rvert < 2.5$			
Leading jet $p_{\text{T}} >$ 45 GeV	Trigger dependent	Leading jet $p_{\text{T}} >$ 45 GeV	Trigger dependent
Event-level selection			
Trigger requirements passed			
Collision vertex reconstructed			
$m_{\tau\tau}^{\text{MMC}} > 60$ GeV			
Opposite-sign electric charges of $e/\mu/\tau_{\text{had-vis}}$ and $\tau_{\text{had-vis}}$			
Exactly two b-tagged jets			
		$m_{bb} < 150$ GeV	

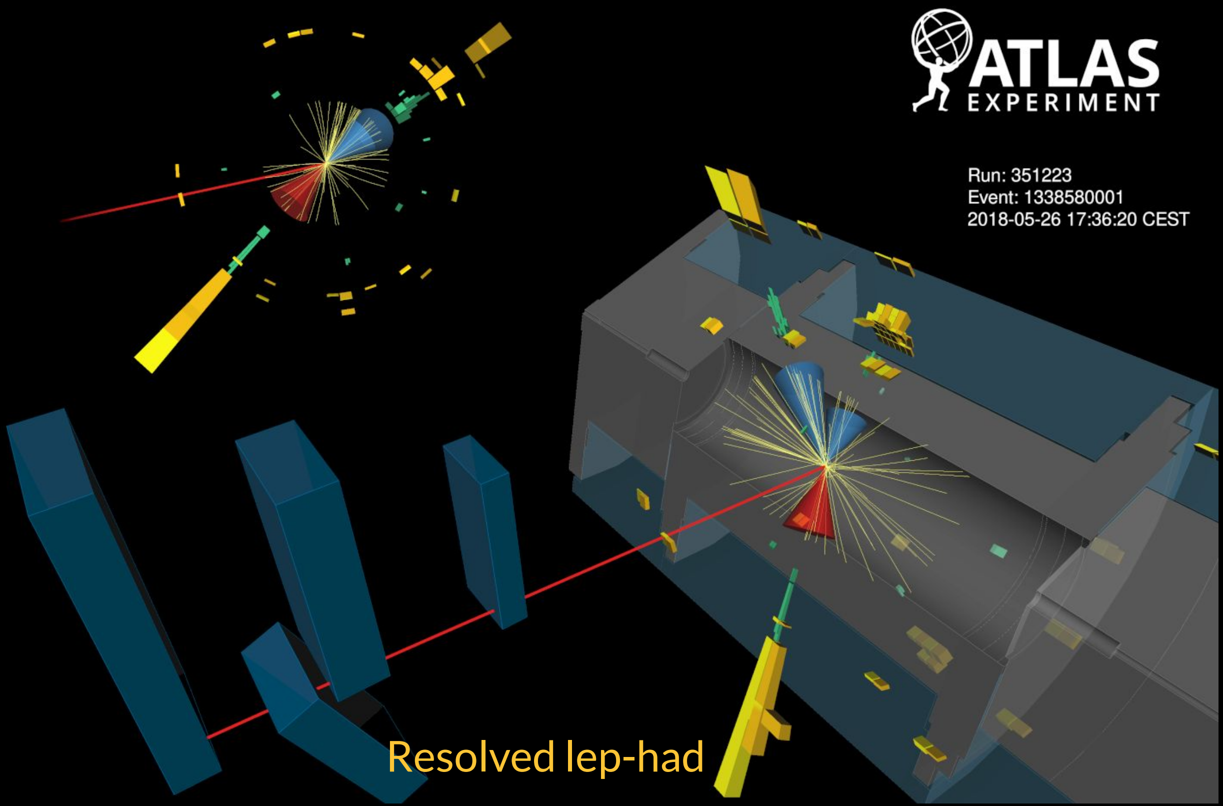
Variable	$\tau_{\text{had}}\tau_{\text{had}}$	$\tau_{\text{lep}}\tau_{\text{had}}$ SLT	$\tau_{\text{lep}}\tau_{\text{had}}$ LTT
m_{HH}	✓	✓	✓
$m_{\tau\tau}^{\text{MMC}}$	✓	✓	✓
m_{bb}	✓	✓	✓
$\Delta R(\tau,\tau)$	✓	✓	✓
$\Delta R(b,b)$	✓	✓	
$\Delta p_{\text{T}}(\ell,\tau)$		✓	✓
Sub-leading b-tagged jet p_{T}		✓	
m_{T}^{W}		✓	
$E_{\text{T}}^{\text{miss}}$		✓	
$\mathbf{p}_{\text{T}}^{\text{miss}}$ ϕ centrality		✓	
$\Delta\phi(\ell\tau, bb)$		✓	
$\Delta\phi(\ell, \mathbf{p}_{\text{T}}^{\text{miss}})$			✓
$\Delta\phi(\tau\tau, \mathbf{p}_{\text{T}}^{\text{miss}})$			✓
S_{T}			✓

$X \to HH \to b\bar{b}\tau^-\tau^+$ (resolved) JHEP 07, 040 (2023)



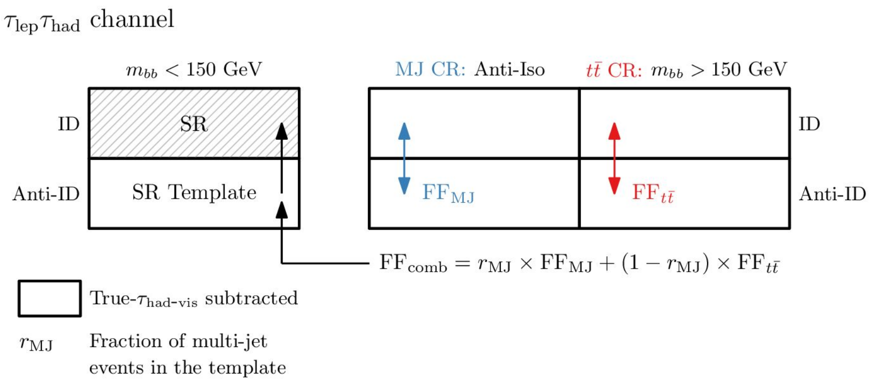
Uncertainty source	Non-resonant HH	Resonant $X \to HH$ 300 GeV	500 GeV	1000 GeV
Data statistical + floating normalisation	81%	76%	90%	93%
Data statistical	81%	76%	90%	93%
$t\bar{t}$ and Z + HF normalisations	4%	8%	3%	5%
Systematic	58%	65%	43%	37%
MC statistical	28%	44%	33%	18%
Experimental	12%	31%	8%	12%
Jet and E_T^{miss}	8%	27%	5%	4%
b-jet tagging	5%	5%	3%	7%
$\tau_{had\text{-}vis}$	6%	12%	3%	8%
Electrons and muons	3%	3%	2%	2%
Luminosity and pile-up	3%	2%	2%	5%
Background and signal and modelling	42%	39%	26%	30%
Fake-$\tau_{had\text{-}vis}$	8%	19%	4%	8%
Top-quark	24%	17%	12%	8%
$Z(\to \tau\tau)$ + HF	9%	17%	9%	15%
Single Higgs boson	29%	2%	14%	15%
Other backgrounds	3%	2%	5%	3%
Signal	5%	14%	7%	15%

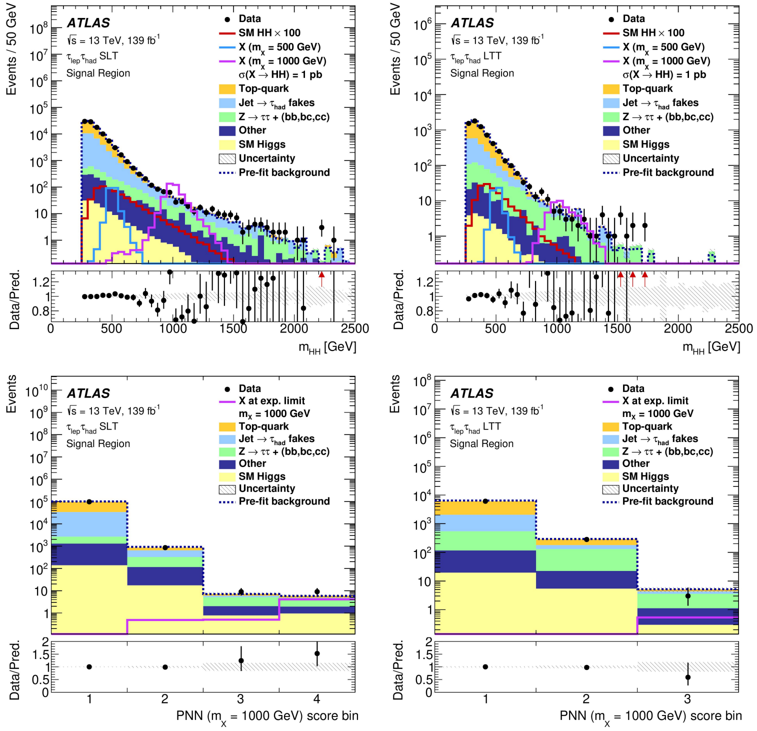
$X \to HH \to b\bar{b}\tau^{-}\tau^{+}$ (lep-had) [JHEP 07, 040 (2023)]



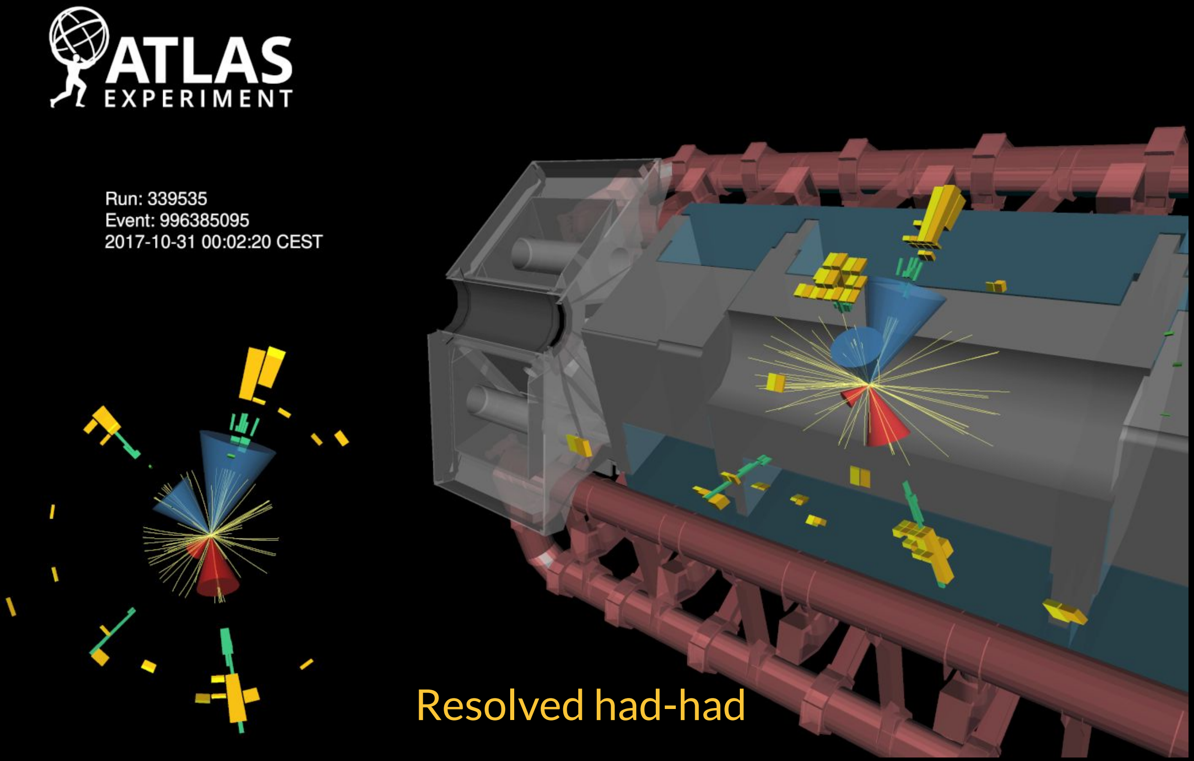
Resolved lep-had

X→HH→$b\bar{b}\tau^-\tau^+$ (lep-had) JHEP 07, 040 (2023)



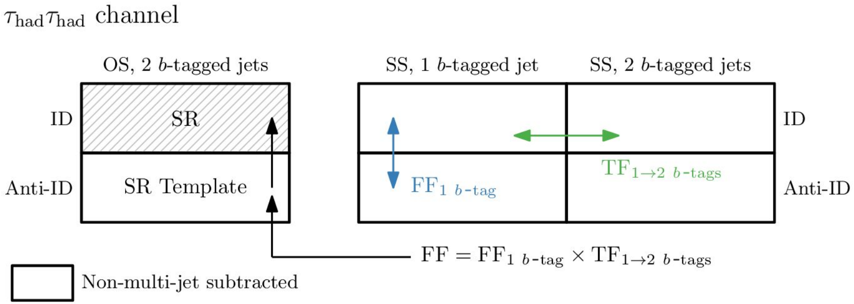


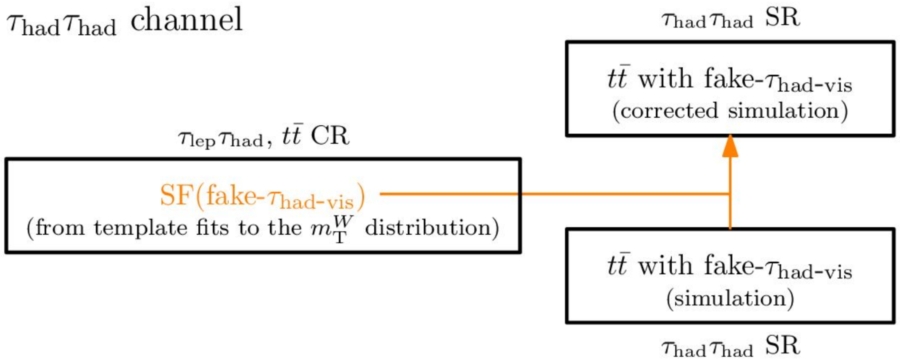
$X \to HH \to b\bar{b}\tau^{-}\tau^{+}$ (had-had) *JHEP 07, 040 (2023)*

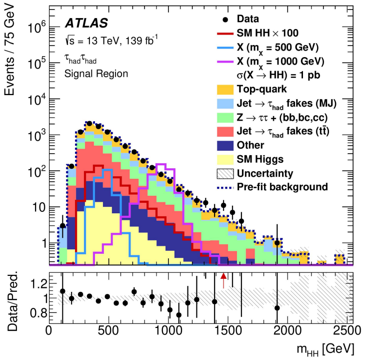


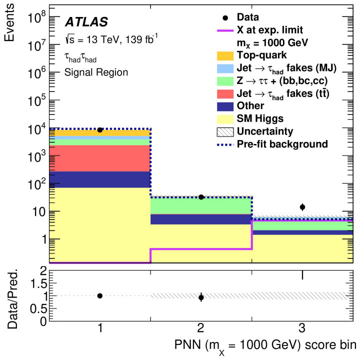
Resolved had-had

X→HH→$b\bar{b}\tau^-\tau^+$ (had-had) [JHEP 07, 040 (2023)]



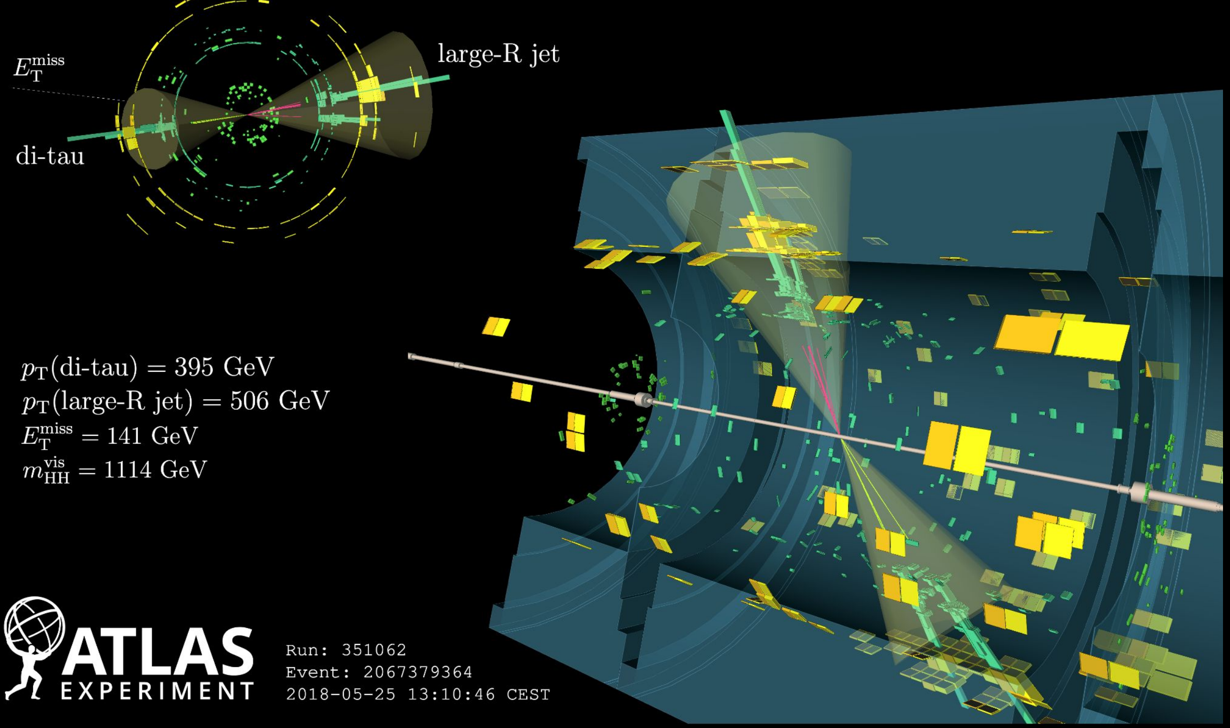




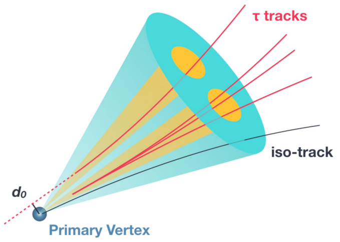


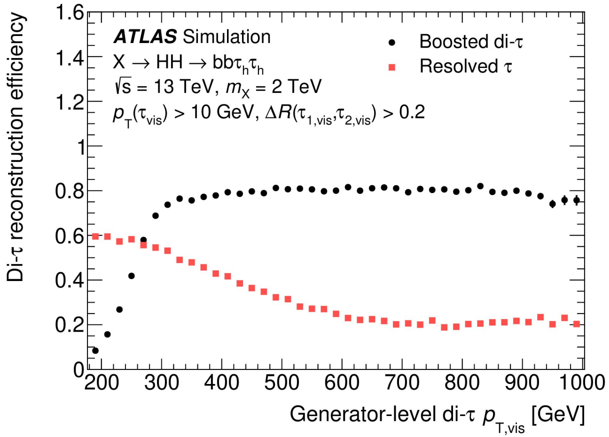
$X \rightarrow HH \rightarrow b\bar{b}\tau^{-}\tau^{+}$ (boosted) [JHEP 11, 163 (2020)]

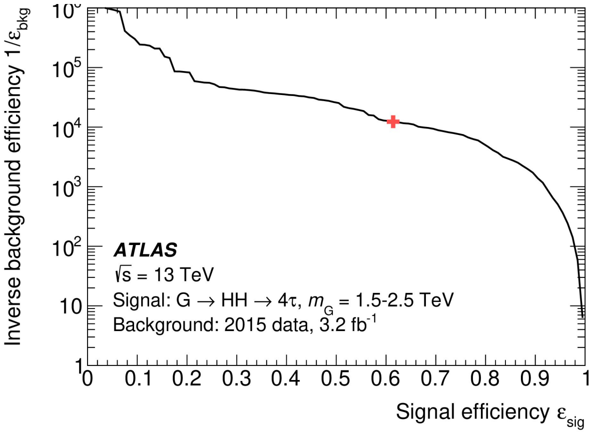
Boosted had-had



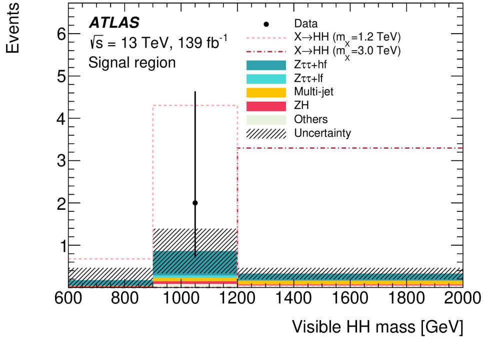
X→HH→$b\bar{b}\tau^-\tau^+$ (boosted) JHEP 11, 163 (2020)

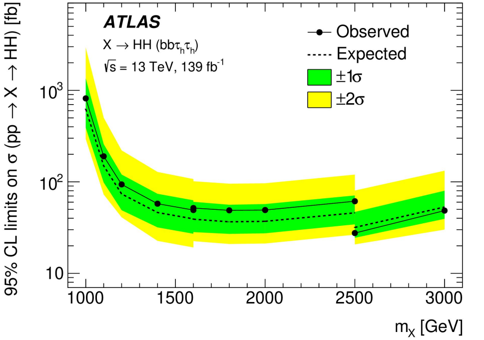




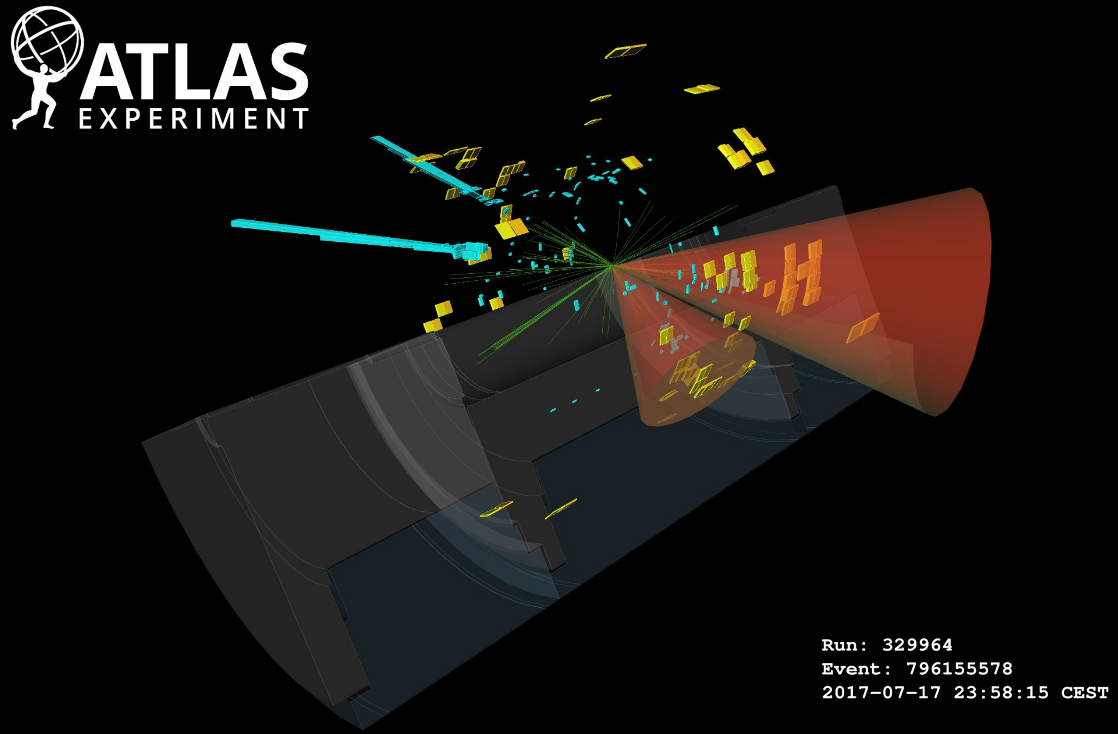


- Focus on construction of new di-τ objects
- Reconstruction:
  - Seeded by untrimmed large-R jet
  - Recluster at least 2 subjets and match tracks
  - di-τ properties calculated from leading two subjects
  - Employ BDT to distinguish true di-τ objects from large-R jets
  - Derive scalefactors for tagger from boosted Z→ττ events
- Signal region selection:
  - 1 b-tagged large-R jet, 1 di-τ jet
  - m(HH, vis) > 900 (1200) GeV if $m_X \geq 1.6$ (2.5) TeV



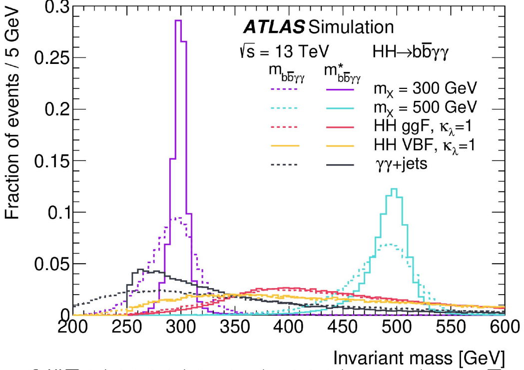


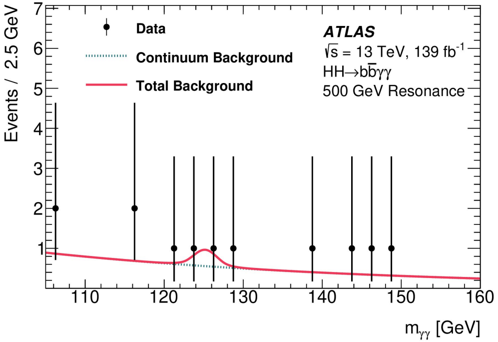
X→HH→$b\bar{b}\gamma\gamma$ Phys. Rev. D 106, 052001 (2022)

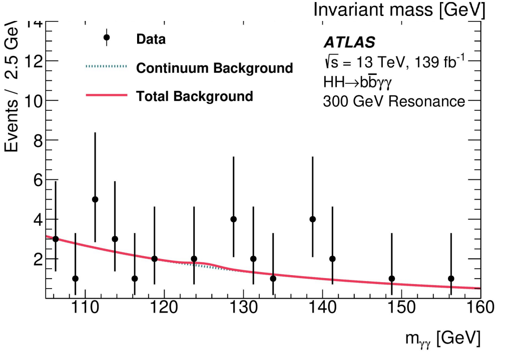


X→HH→$b\bar{b}\gamma\gamma$ Phys. Rev. D 106, 052001 (2022)

- Invariant mass definition $m(b\bar{b}\gamma\gamma)^* = m(b\bar{b}\gamma\gamma) - m(b\bar{b}) - m(\gamma\gamma) + 250\,\mathrm{GeV}$
- $$\mathrm{BDT_{tot}} = \frac{1}{\sqrt{C_1^2 + C_2^2}} \sqrt{C_1^2 \left(\frac{\mathrm{BDT}_{\gamma\gamma} + 1}{2}\right)^2 + C_2^2 \left(\frac{\mathrm{BDT}_{\mathrm{Single}H} + 1}{2}\right)^2}.$$ with $C_1 = 1 - C_2 = 0.65$
- Cut value on BDT based on m_X





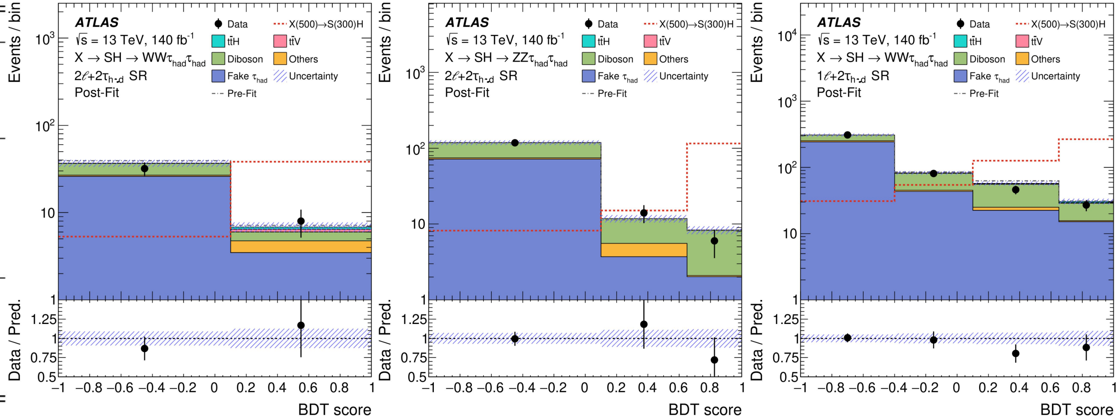


Variable	Definition
Photon-related kinematic variables	
$p_T^{\gamma\gamma}$, $y^{\gamma\gamma}$	Transverse momentum and rapidity of the diphoton system
$\Delta\phi_{\gamma\gamma}$ and $\Delta R_{\gamma\gamma}$	Azimuthal angle and ΔR between the two photons
Jet-related kinematic variables	
$m_{b\bar{b}}$, $p_T^{b\bar{b}}$ and $y_{b\bar{b}}$	Invariant mass, transverse momentum and rapidity of the b-tagged jets system
$\Delta\phi_{b\bar{b}}$ and $\Delta R_{b\bar{b}}$	Azimuthal angle and ΔR between the two b-tagged jets
N_{jets} and $N_{b\text{-jets}}$	Number of jets and number of b-tagged jets
H_T	Scalar sum of the p_T of the jets in the event
Diphoton+dijet-related kinematic variables	
$m^*_{b\bar{b}\gamma\gamma}$	Invariant mass of the diphoton plus b-tagged jets system
$\Delta y_{\gamma\gamma,b\bar{b}}$, $\Delta\phi_{\gamma\gamma,b\bar{b}}$ and $\Delta R_{\gamma\gamma,b\bar{b}}$	Distance in rapidity, azimuthal angle and ΔR between the diphoton and the b-tagged jets system
Missing transverse momentum variables	
E_T^{miss}	Missing transverse momentum

		Relative impact of the systematic uncertainties [%]	
Source	Type	Nonresonant analysis HH	Resonant analysis $m_X = 300$ GeV
Experimental			
Photon energy resolution	Norm. + Shape	0.4	0.6
Jet energy scale and resolution	Normalization	< 0.2	0.3
Flavor tagging	Normalization	< 0.2	0.2
Theoretical			
Factorization and renormalization scale	Normalization	0.3	< 0.2
Parton showering model	Norm. + Shape	0.6	2.6
Heavy-flavor content	Normalization	0.3	< 0.2
$\mathcal{B}(H \to \gamma\gamma, b\bar{b})$	Normalization	0.2	< 0.2
Spurious signal	Normalization	3.0	3.3

X→SH→VVτ⁻τ⁺ arXiv:2307.11120 (2023)

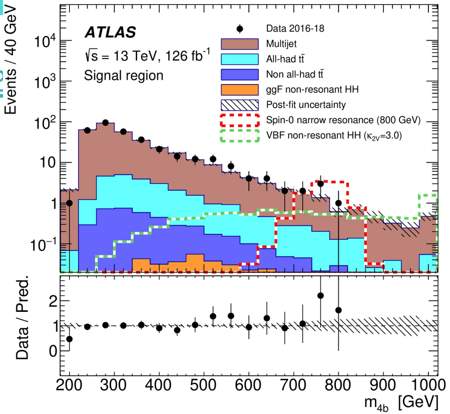
Channels	Selections
$WW1\ell2\tau_{\rm had}$	exactly one light lepton (electron or muon): $p_{\rm T} > 27$ GeV, $\lvert\eta\rvert < 2.5$ exactly two RNN medium $\tau_{\rm had}$ with opposite-sign: $p_{\rm T} > 20$ GeV, $\lvert\eta\rvert < 2.5$ ΔR between two $\tau_{\rm had}$ candidates: $\Delta R_{(\tau_0,\tau_1)} \leq 2$ number of jets and b-jets: $N_{\rm jets} \geq 2$ and $N_{b-{\rm jets}} == 0$
$WW2\ell2\tau_{\rm had}$	exactly two light leptons with opposite-sign: $p_{\rm T} > 10$ GeV, $\lvert\eta\rvert < 2.5$ exactly two RNN medium $\tau_{\rm had}$ with opposite-sign: $p_{\rm T} > 20$ GeV, $\lvert\eta\rvert < 2.5$ invariant dilepton mass: $m_{\ell\ell} > 12$ GeV Z-veto ($\lvert m_{\ell\ell} - m_Z\rvert > 10$ GeV) for same-flavour leptons $\Delta R_{(\tau_0,\tau_1)} \leq 2$ $N_{b-{\rm jets}} == 0$
$ZZ2\ell2\tau_{\rm had}$	exactly two same-flavour light leptons with opposite-sign: $p_{\rm T} > 10$ GeV, $\lvert\eta\rvert < 2.5$ exactly two RNN medium $\tau_{\rm had}$ with opposite-sign: $p_{\rm T} > 20$ GeV, $\lvert\eta\rvert < 2.5$ Z-peak selection ($\lvert m_{\ell\ell} - m_Z\rvert < 10$ GeV) $\Delta R_{(\tau_0,\tau_1)} \leq 2$ $N_{b-{\rm jets}} == 0$



Variable	Definition	WW $1\ell2\tau_{\rm had}$	WW $2\ell2\tau_{\rm had}$	ZZ $2\ell2\tau_{\rm had}$
$m_{\rm X,\ truth}$	generated mass of generated X particle	×	×	×
$\Delta R(\tau\tau, \ell_0)$	angular distance between the leading lepton and the $\tau\tau$ system	×	×	×
$\min(\Delta R(\tau\tau, {\rm j}))$	minimum angular distance between a jet and the $\tau\tau$ system	×	-	-
$\Delta R(\ell, \ell)$	angular distance between two leptons	-	×	×
$\Delta\phi(\tau\tau, E_T^{\rm miss})$	azimuthal angle between the $\tau\tau$ system and $E_T^{\rm miss}$	×	×	×
$E_T^{\rm miss} + \Sigma p_{\rm T}({\rm jets})$	sum of $E_T^{\rm miss}$ momentum and $p_{\rm T}$ of jets	-	-	×
$p_{{\rm T}\tau 0}$	leading tau-lepton $p_{\rm T}$	×	×	×
$m_{\tau\tau}$	visible invariant mass of the $\tau\tau$ system	×	×	×
$m_{\ell\ell}$	invariant mass of the dilepton system	-	×	-
$\min(\Delta R(\ell, {\rm j}))$	minimum angular distance between a jet and the lepton	×	-	-
$\min(\Delta R({\rm j}, {\rm j}))$	minimum angular distance between two jets	×	-	-
$p_{{\rm T}\tau 1}$	subleading τ-lepton $p_{\rm T}$	×	×	×
$m_{\rm T}^W$	transverse mass calculated from the lepton(s) and $E_T^{\rm miss}$ in the event	×	×	×
dilep_type	dilepton type: one of $\mu\mu$, $e\mu$, μe, ee	-	×	-

Source of uncertainty	$\Delta\sigma/\sigma(pp \to X \to SH)$ [%] $m_X = 500$, $m_S = 300$ [GeV]	$m_X = 1250$, $m_S = 300$ [GeV]
Lepton ID	5	1
JES and JER	6	4
MC modelling	11	9
Fake τ modelling	10	5
τ ID	11	6
Luminosity and triggers	3	2
MC (CR) statistics	8	5
Total systematic uncertainty	27	15
Data statistical uncertainty	46	40
Total uncertainties	53	43

VBF jjX→jjHH→jjb$\bar{b}$b$\bar{b}$ JHEP 07, 108 (2020) (Err. 2

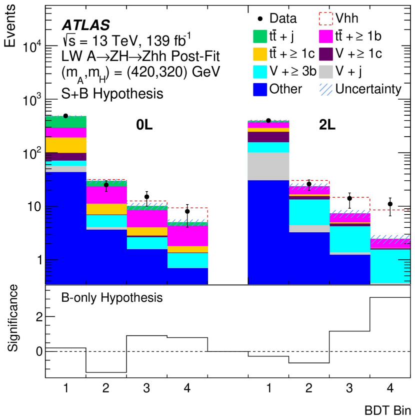


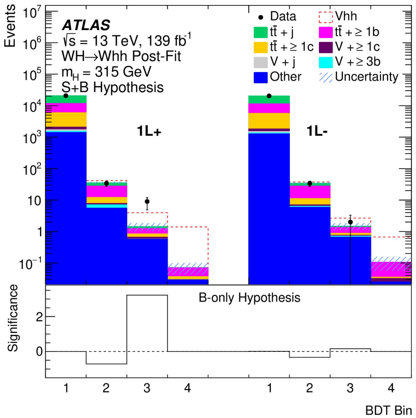
	Selections	
VBF topology	At least two jets with $p_T > 30$, $\|\eta\| > 2.0$	Two highest-p_T jets with opposite sign η
		$\|\Delta\eta_{jj}^{VBF}\| > 5.0$ and $m_{jj}^{VBF} > 1000$
Signal topology	Exactly 4 b-tagged jets with $p_T > 40$, $\|\eta\| < 2.0$	
	If $m_{4b} < 1250$	$\frac{360}{m_{4b}} - 0.5 < \Delta R_{bb}^{lead} < \frac{653}{m_{4b}} + 0.475$
		$\frac{235}{m_{4b}} < \Delta R_{bb}^{subl} < \frac{875}{m_{4b}} + 0.35$
	If $m_{4b} \geq 1250$	$\Delta R_{bb}^{lead} < 1$
		$\Delta R_{bb}^{subl} < 1$
	Pairs with minimum $D_{HH} = \sqrt{(m_{2b}^{lead})^2 + (m_{2b}^{subl})^2}\left\|\sin\left(\tan^{-1}\left(\frac{m_{2b}^{subl}}{m_{2b}^{lead}}\right) - \tan^{-1}\left(\frac{116.5}{123.7}\right)\right)\right\|$	
Background rejection	Multijet	$\|\Delta\eta_{HH}\| < 1.5$
		$\|\Sigma_i \vec{p}_{T i}\| < 60$, where i = b-jets and VBF-jets
		$p_{T,H}^{lead} > 0.5 m_{4b} - 103$
		$p_{T,H}^{subl} > 0.33 m_{4b} - 73$
	$t\bar{t}$	Veto if $X_{Wt} = \sqrt{\left(\frac{m_W - 80.4}{0.1 m_W}\right)^2 + \left(\frac{m_t - 172.5}{0.1 m_t}\right)^2} \leq 1.5$
Region definition	Signal region (SR)	$X_{HH} = \sqrt{\left(\frac{m_{2b}^{lead} - 123.7}{11.6}\right)^2 + \left(\frac{m_{2b}^{subl} - 116.5}{18.1}\right)^2} < 1.6$
	Validation region (veto SR)	$\sqrt{\left(m_{2b}^{lead} - 123.7\right)^2 + \left(m_{2b}^{subl} - 116.5\right)^2} < 30$
	Sideband region (veto SR, VR)	$\sqrt{\left(m_{2b}^{lead} - 123.7\right)^2 + \left(m_{2b}^{subl} - 116.5\right)^2} < 45$

Source	m_X = 300 GeV	Source	m_X = 800 GeV
Multijet normalisation	46%	Multijet modelling	44%
Jet energy resolution	26%	Jet energy resolution	23%
Multijet modelling	18%	Jet energy scale	19%
Multijet kinematic reweighting	17%	Multijet kinematic reweighting	9%
$t\bar{t}$ modelling	11%	Multijet normalisation	7%
Jet energy scale	10%	$t\bar{t}$ modelling	6%
Total systematic uncertainty	64%	Total systematic uncertainty	57%
Statistical uncertainty	77%	Statistical uncertainty	82%

VX→VHH→Vbb̄bb̄ Eur. Phys. J. C 83, 519 (2023)

	Signal regions			Control regions	
	0L	1L (1L+/1L−)	2L	$t\bar{t}$	V + jets
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	single-lepton	single-lepton	single-lepton	single-photon
Lepton or photon	0 *loose* leptons, 0 identified τ_h	= 1 *tight* electron with $p_{\mathrm{T}} > 27$ GeV OR 1 *medium* muon with $p_{\mathrm{T}} > 25$ GeV, 0 additional *loose* leptons, 0 identified τ_h	= 2 *loose* leptons (e^+e^- or $\mu^+\mu^-$), ≥ 1 lepton with $p_{\mathrm{T}} > 27$ GeV, $81 < m_{\ell\ell} < 101$ GeV	= 2 *loose* leptons ($e^{\pm}\mu^{\mp}$), ≥ 1 lepton with $p_{\mathrm{T}} > 27$ GeV	= 1 photon with $p_{\mathrm{T}} > 150$ GeV, 0 *loose* leptons, 0 identified τ_h
$\boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV, $S(E_{\mathrm{T}}^{\mathrm{miss}}) > 12$, $\lvert\Delta\phi(\boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}, h)\rvert > 1$	$E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV	—	—	—
Jets	≥ 4 jets with $p_{\mathrm{T}} > 20$ GeV and passing the 85% b-tagging WP				





	Channel and signal model							
	0L			1L		2L		
Variable	Vhh	VH	$A \to ZH$	Vhh	VH	Vhh	VH	$A \to ZH$
$m_{h_1} + m_{h_2}$	✓	✓	✓	✓	✓	✓	✓	✓
$m_{h_1} - m_{h_2}$	✓	✓	✓	✓	✓	✓	✓	✓
N_{jets}	✓	✓	✓	✓	✓	✓	✓	✓
$H_{\mathrm{T}}^{\mathrm{ex}}$	✓	✓	✓	✓	✓	✓	✓	✓
$\sum s_{b\text{-tag}}^{\mathrm{pc}}$	✓	✓	✓	✓	✓	✓	✓	✓
$m_{h_1}^{\mathrm{FSR}}$	✓	✓	✓	✓	✓	✓	✓	✓
$m_{h_2}^{\mathrm{FSR}}$	✓	✓	✓	✓	✓	✓	✓	✓
m_{hh}	✓			✓		✓		
p_{T}^{hh}	✓	✓		✓	✓	✓	✓	
$E_{\mathrm{T}}^{\mathrm{miss}}$	✓	✓		✓	✓	✓	✓	✓
p_{T}^{V}				✓	✓	✓	✓	
m_{T}^{W}				✓				
$\cosh(\Delta\eta)_1 - \cos(\Delta\phi)_1$	✓	✓		✓	✓	✓	✓	
$\cosh(\Delta\eta)_2 - \cos(\Delta\phi)_2$	✓	✓		✓	✓	✓	✓	
$\lvert y_{h_1} - y_{h_2}\rvert$	✓	✓		✓	✓	✓	✓	
$\lvert y_V - y_{hh}\rvert$						✓	✓	

VX→VHH→Vb$\bar{b}$b$\bar{b}$ Eur. Phys. J. C 83, 519 (2023)

Model	Vhh like in SM	WH	ZH	NW $A \to ZH$	LW $A \to ZH$
Systematic uncertainty source			$\Delta\mu/\mu$ [%]		
Background modelling	+20, −15	+14, −11	+4.7, −3.0	+17, −13	+20, −18
MC statistics	+12, −9.1	+13, −7.8	+4.8, −2.2	+7.2, −4.1	+10, −8.3
Objects	+12, −8.6	+8.0, −5.2	+4.5, −2.2	+19, −11	+16, −12
Signal modelling	+10, −4.7	+12, −4.9	+8.6, −3.0	+14, −5.1	+17, −7.6
VR non-closure	+14, −11	+11, −9.4	+4.4, −3.0	+4.9, −3.7	+12, −10
Total systematic uncertainty	+30, −22	+27, −18	+12, −5.8	+30, −18	+33, −24
Statistical uncertainty	+44, −39	+52, −43	+68, −49	+59, −47	+42, −37
Total	+52, −44	+59, −47	+69, −49	+66, −50	+53, −45