UNIVERSITY OF MICHIGAN

Searches for BSM Scalars at ATLAS

Nicholas Graves Kyriacou

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On behalf of the ATLAS Collaboration
University of Michigan

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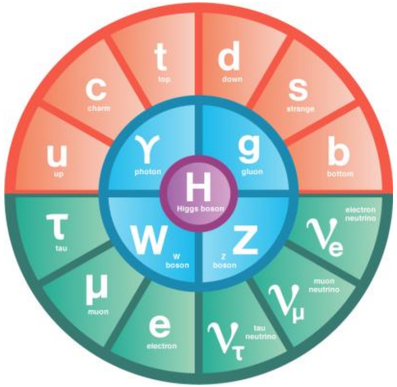
Motivation

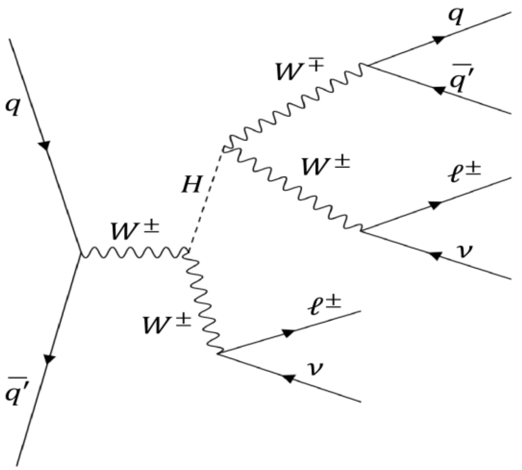
- Searches for Beyond the Standard Model (BSM) physics remain a key component of the LHC physics programme.
- Vast parameter-space of BSM scenarios under exploration, focus on ***Scalar*** resonance decays.
  - Axion-like Particles (ALP's)
  - Light pseudo-scalars (Hidden Abelian Higgs Models)
  - 2(3)HDM Searches
  - Next-to-Minimal Supersymmetric SM (NMSSM)
  - Randall-Sundrum Model
  - (Higgs) EFT-Intepretations
- *All analysis presented use full Run-2 dataset.

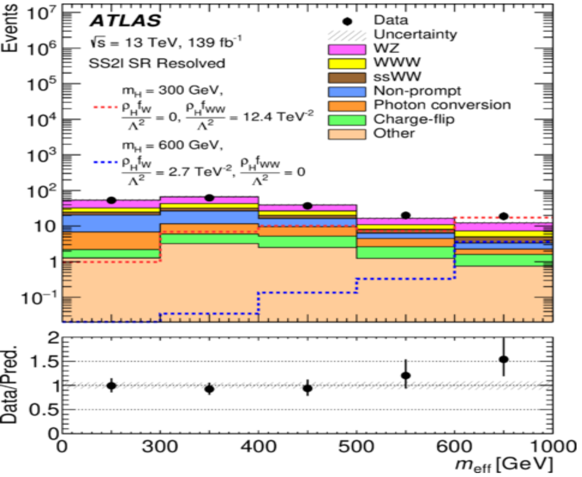
Scalar Signature	Final-State
$W^{\pm}$H	$l^{\pm}\nu l^{\pm}\nu jj$
X	$\gamma\gamma$
$X^{\pm}, X^{0}$	$W^{\pm}\gamma, Z\gamma$
a	$\mu\mu$
$X \rightarrow SH$	$VV\tau\tau$
$H^{\pm}b(W^{\mp}b)$	$cbb(l\nu b)$
A→Z(H)	$ll(t\bar{t})/\nu\bar{\nu}(b\bar{b})$
Vhh	$b\bar{b}b\bar{b}$ $(l\nu),(\nu\nu),(ll)$
X^{0}	WW,WW(jj), ZZ, ZZ(jj)

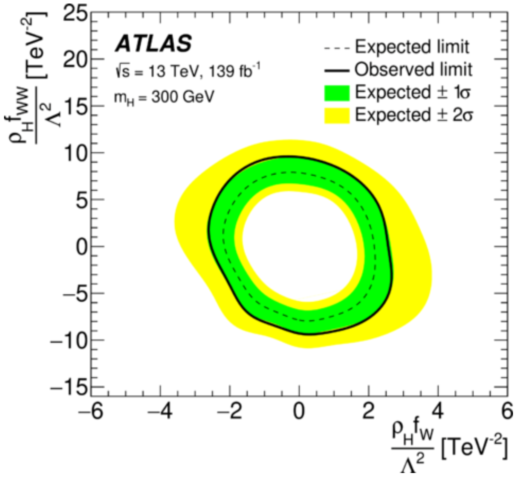


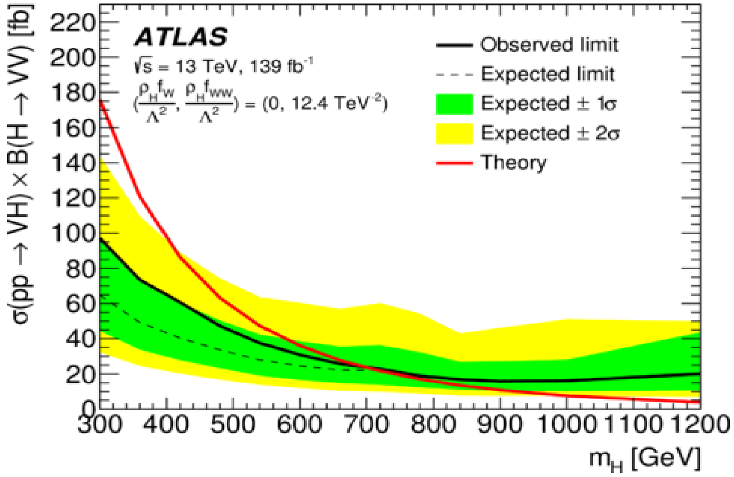
$W^{\pm}H \rightarrow W^{\pm}W^{\pm}W^{\mp}$

- Model-Independent search for heavy higgs production in association with a vector-boson. (arXiv:2211.02617)
  - Targets same-sign di-lepton final state $W^{\pm}W^{\pm}W^{\mp} \rightarrow l^{\pm}\nu l^{\pm}\nu jj$
  - Includes EFT interpretations, scanning across (f_W, f_{WW})
    - Model-Independent, Higgs, m_H: $(0.3 \rightarrow 1.5\ \mathrm{TeV})$





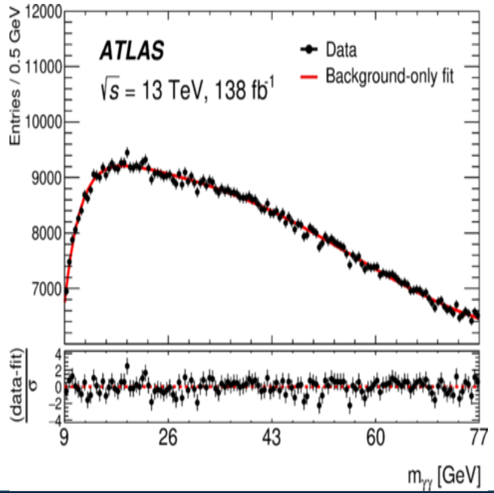


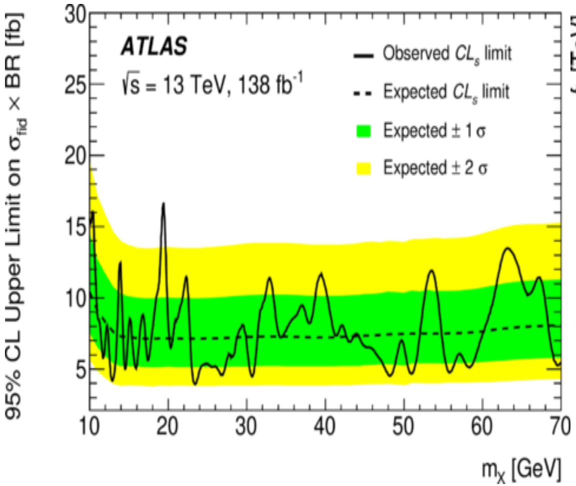


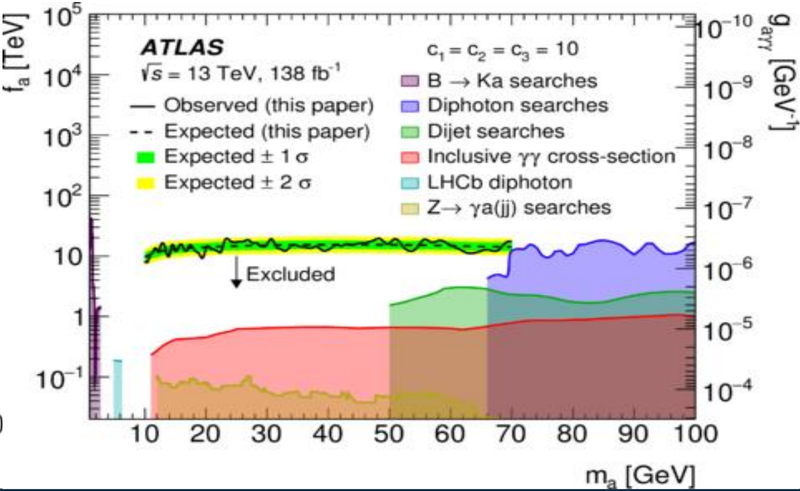
Boosted Di-photon Resonance Search

arXiv:2211.04172

- Probes low-mass range by targeting closely spaced photons with $p_T^{\gamma\gamma}$>50 GeV to overcome trigger thresholds.
  - Prior searches cover only $m_{\gamma\gamma}$ > 65 GeV
- Highest observed excess at m_x=19.4 GeV 3.1σ local (1.5σ global)

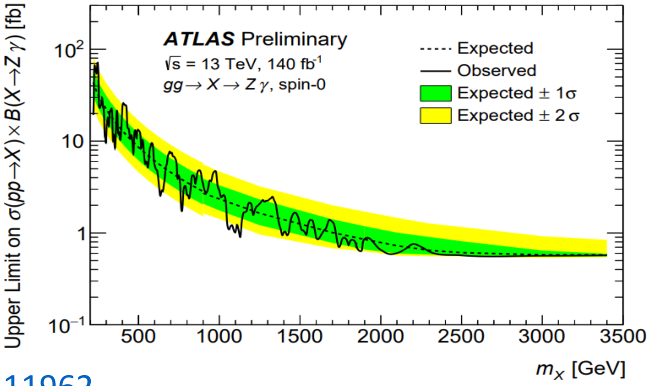


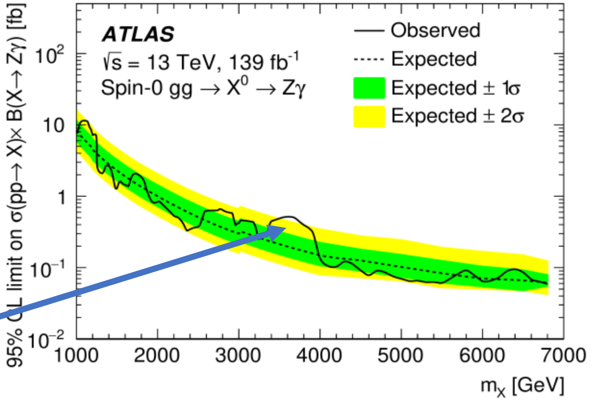




High Mass $W\gamma/Z\gamma$ Resonances

- Searches for charged, and neutral resonances, probing V decays in boosted channel.
  - $q\overline{q'} \to X^{\pm} \to W^{\pm}\gamma$ ***(Spin-1)***
  - $gg(q\bar{q}) \to X^0 \to Z\gamma$ ***Spin-0/(2)***
- 2 sets of complimentary analysis
  - **Hadronic Z decay** (Large-R jet) arXiv:2304.11962
    - Best sensitivity for M_x > 2 TeV
  - **Leptonic Z decay (NEW RESULT!) ATLAS-CONF-2023-030**
    - Utilizes dedicated MVA to improve sub leading electron identification
  - **Analytical function to model background**
- No significant deviations of data from predicted background observed
  - Largest local significance (2.5σ) @ m_X=3640 GeV (**Z-Hadronic**)

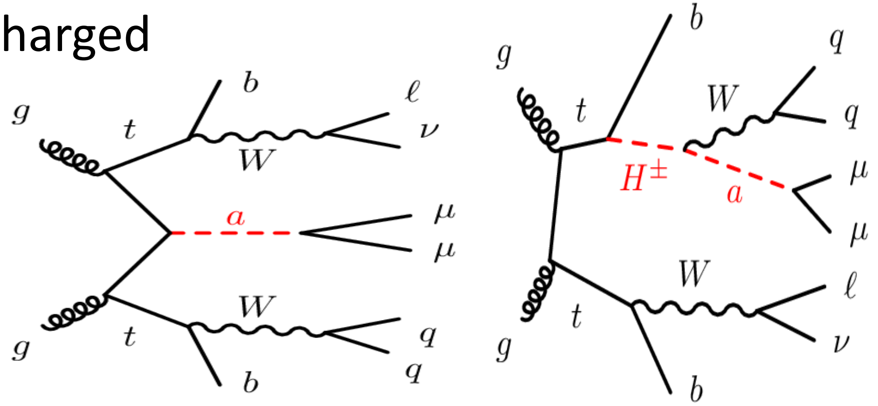


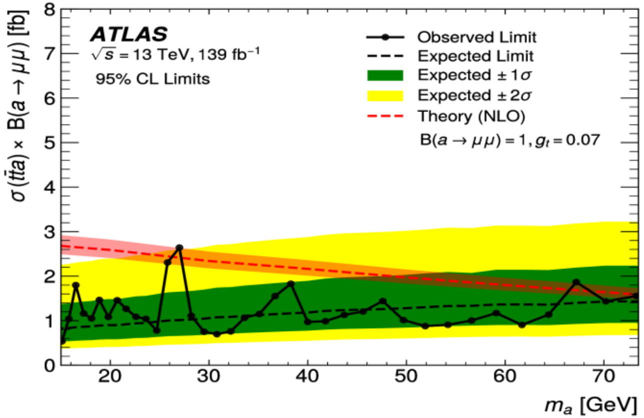


a→ $\mu\mu$ in association w/ $t\bar{t}$

NEW RESULT!
arXiv:2304.14247

- Direct pseudo-scalar production, and via charged Higgs boson decay.
- Targets di-muon decays, for high mass resolution.
  - 15<m_a<72 GeV & 120<m_{H^+}< 160 GeV
- Overall no significant excesses observed
  - Excess at m_a=27 GeV → 2.7σ (local)
- Set $\sigma(t\bar{t}a)$B(a →$\mu\mu$) upper-limits
  - (0.5 - 3) fb @ 95% CL
- Set B(t → bH^+ → W^+a → $\mu\mu$) upper-limits
  - (0.9 - 3.9) x 10^{-6}@ 95% CL (see backup)

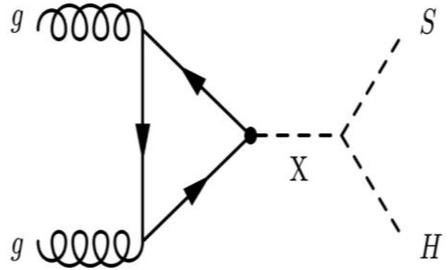


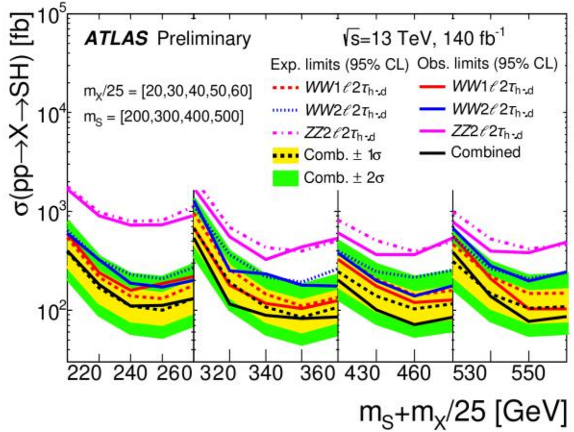


$X \to SH \to VV(\tau\tau)$

NEW RESULT!
ATLAS-CONF-2023-031

- Probes $H \to \tau\tau$(hadronic) and V → (leptonically)
  - Explores $M_X \to \{500,1500\}$ GeV, $M_S \to \{200,500\}$ GeV parameter-space
  - Targets (ZZ) $2l2\tau_{had}$, (WW) $2l2\tau_{had}$, (WW) $1l2\tau_{had}$ final states
- V+jets – fake τ_{had} dominant background
  - Estimated with FF method
  - B-jet veto for background suppression
- Utilizes BDT discriminant parametrized over M_X
- Production x-section upper limits derived (@ 95%CL):
  - $\sigma(pp \to X \to SH)$ 72 ⇔ 542 fb's
  - $\sigma(pp \to X \to SH \to ZZ\tau\tau)$ 6 ⇔ 33 fb's
  - $\sigma(pp \to X \to SH \to WW\tau\tau)$ 3 ⇔ 26 fb's

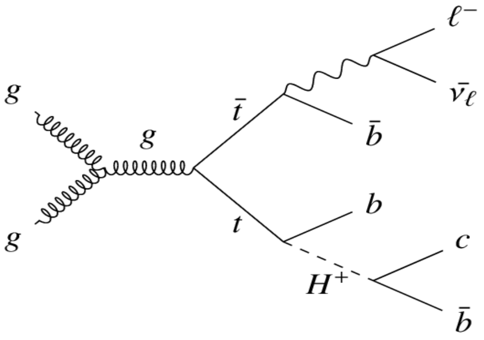


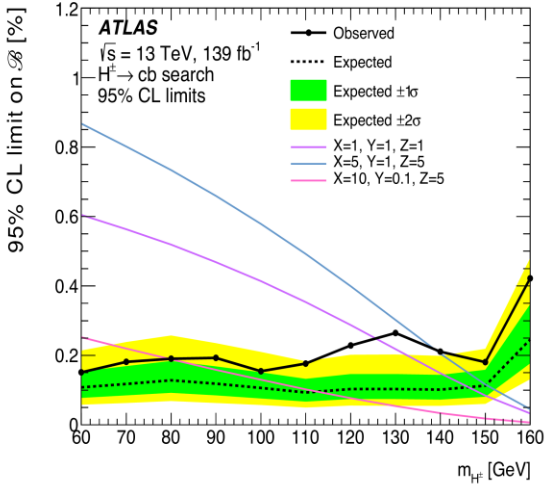


Light, charged Higgs Production

arXiv:2302.11739

- Search for $t\bar{t} \rightarrow H^{\pm}b(W^{\mp}b) \rightarrow cbb(l\nu b)$
  - 3HDM interpretations cast
- Segments analysis regions based on jet and b-jet multiplicities
  - Allows data-driven corrections to $t\bar{t}$ (mis)modelling
- Employs NN (parametrized over $m_{H^{\pm}}$) discriminant for enhanced signal-background separation
- Largest excess: $m_{H^{\pm}}$= 130 GeV
  - Local (global) significance 3σ (2.5σ)
- Upper-limits on Br($t \rightarrow H^{\pm}b$)x Br($H^{\pm} \rightarrow cb$) derived
  - (0.15 – 0.42)% for 60<$m_{H^{\pm}}$<160 GeV (assuming SM $t\bar{t}$ production)
  - Similar CMS-search reports upper-limits of ~(0.8-0.5)% for 90<$m_{H^{\pm}}$<150 GeV

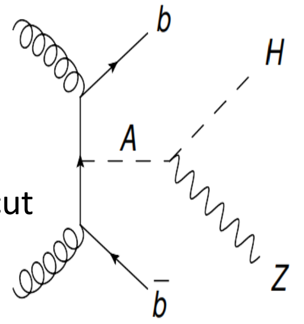


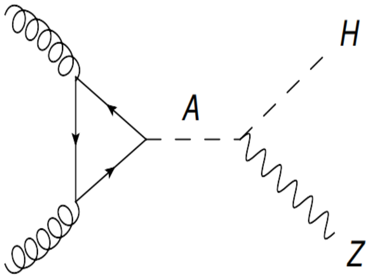


(CP-odd) A→ZH (Heavy Higgs)

NEW RESULT!
[ATLAS-CONF-2023-034]

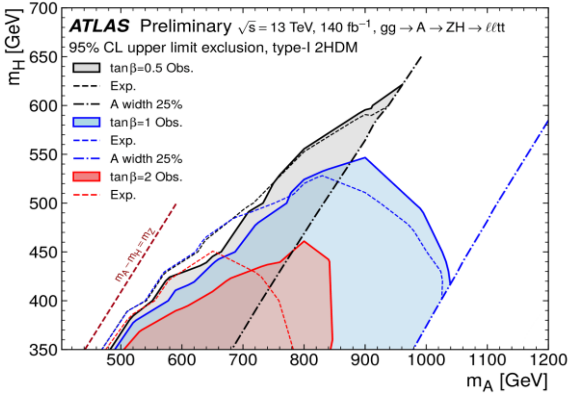
- Prior A → ZH searches look for Z → ll, H → $b\bar{b}$,WW,$\tau\tau$,hh
- Probes (2) novel final-states A→Z(H) → $ll(t\bar{t})/v\bar{v}(b\bar{b})$
    - Search covers (m_A, m_H) > (800,300) GeV (narrow-width H)
- $ll(t\bar{t})$ Channel
    - Exactly 3 leptons, 2 b-jets, and ≥ 4 jets, (sliding) mass window $\left|M_{\mathrm{H}}^{\mathrm{Cand}} - M_{\mathrm{H}}^{\mathrm{hypo}}\right|$ cut
    - Targets unexplored $\mathrm{m_H} > 2{*}\mathrm{m_{top}}$ parameter-space
    - Novel LHC search at 13 TeV!
- $v\bar{v}(b\bar{b})$
    - ≥ 2 jets, (==2 or ≥ 3) b-tag jets categories
    - E_T^{Miss} > 150 GeV, (sliding) mass window $\left|M_{\mathrm{H}}^{\mathrm{Cand}} - M_{\mathrm{H}}^{\mathrm{hypo}}\right| < 0.2 * M_{\mathrm{H}}^{\mathrm{hypo}}$
    - First LHC search for high $m_{b\bar{b}}$ resonances + MET
- Search effectively probes m_H > 350 GeV and high m_A for m_H < 350 GeV

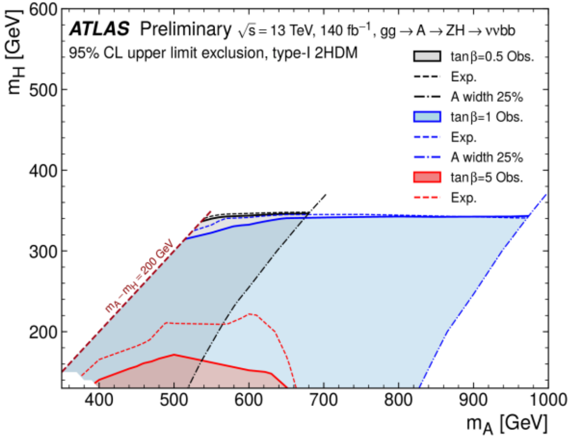


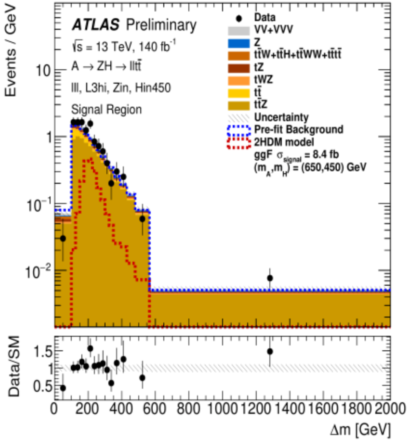


(CP-odd) A→ZH (Heavy Higgs) Results

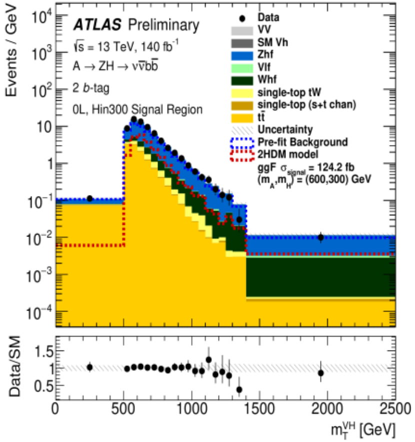
- Binned profile likelihood of m_A-m_H $(llt\bar{t})$, m_T^A $(vvb\bar{b})$
  - No significant data excesses from bkg-only hypothesis found
    - Small Excess: (m_A, m_H) = (650,450) GeV in $llt\bar{t}$-channel w/ 2.85σ (local)



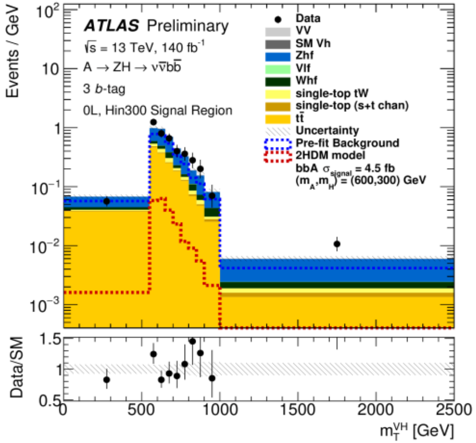




$llt\bar{t}$



$vvb\bar{b}$, 2 b-tag



$vvb\bar{b}$, $\geq$3 b-tag

Resonant and SM Vhh Production

arXiv:2210.05415

- Search for Higgs boson pair-production in association with a V boson
  - Targets $hh \rightarrow b\bar{b}b\bar{b}$ w/ (W/Z) $\rightarrow lv, vv, ll$ final states
- Probes VH→ Vhh (Higgstrahlung) & A→ZH (2HDM)
  - Overall several data-excesses observed!

Large excess @ (m_A, m_H) = (420,320) GeV
- local (global) 3.8σ (2.8σ)

95%-CL Upper-limit couplings **(ATLAS)**

-34.4 (-24.1) < K_λ < 33.3 (22.9)

-8.6 (-5.7) < K_{2V} < 10.0 (7.1)

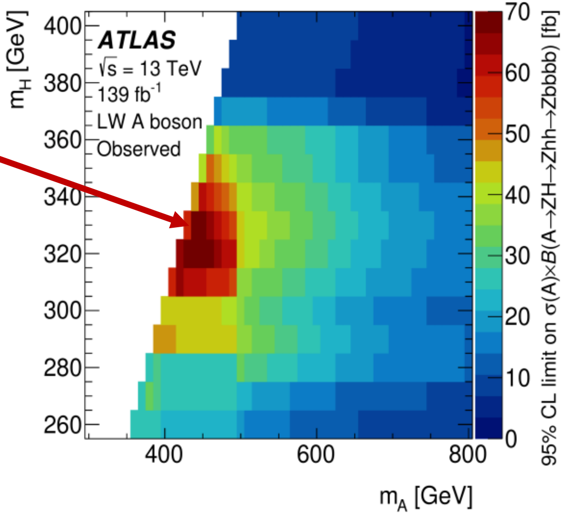
μ_{obs} (exp) = 183 (87^{+41}_{-24})

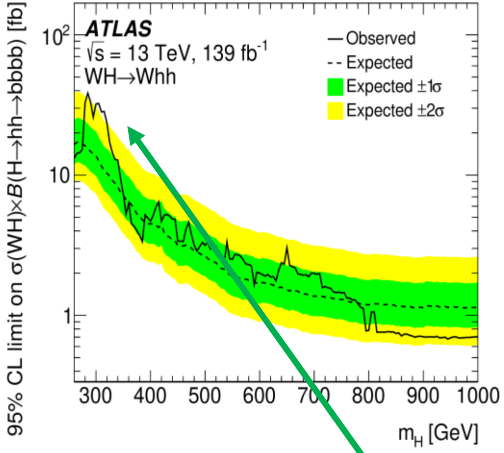
95%-CL Upper-limit couplings **(CMS)**

-37.7 (-30.1) < K_λ < 37.2 (28.9)

-12.2 (-7.64) < K_{2V} < 13.5 (8.9)

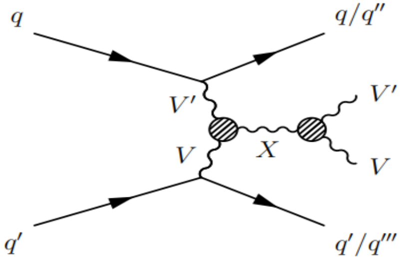
μ_{obs} (exp) = 294 (124)





Small excess @ (m_H) = (315) GeV
- local (global) 2.5σ (1.3σ)

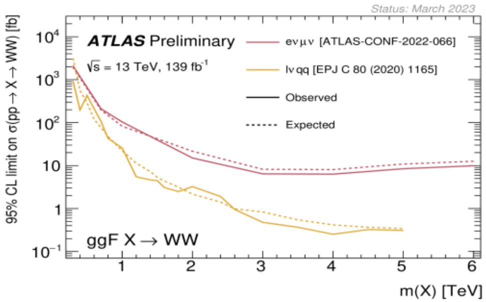
Di-boson Resonance Summary

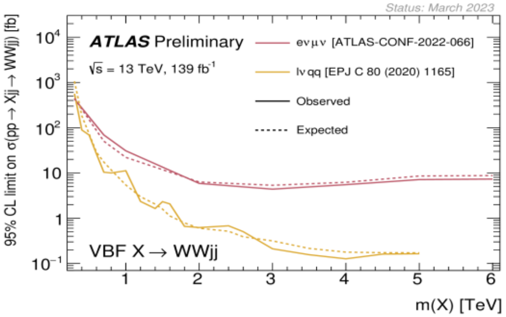


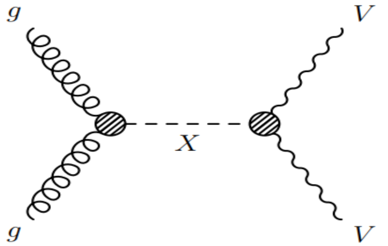
- Summary of all ATLAS Run-2 di-boson searches
  - **WW**, WZ, **ZZ**, WH, ZH, $\gamma\gamma$.

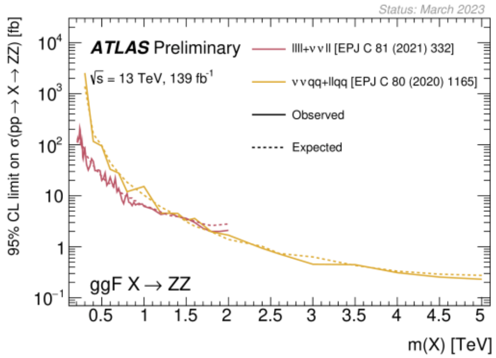
[ATL-PHYS-PUB-2023-007]

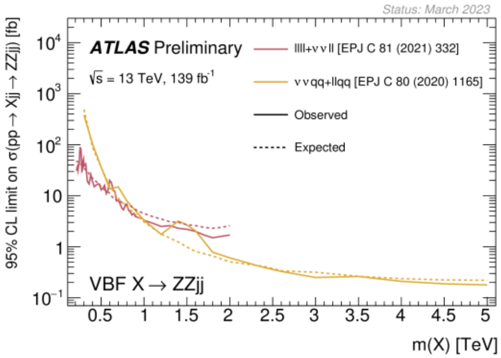
95% CL-Exclusion limits for X→WW in ggF (Left) and VBF (Right) production. (Interpreted in context of RS-model)











95% CL-Exclusion limits for X→ZZ in ggF (Left) and VBF (Right) production. (Interpreted in context of narrow-width X approximation)

Closing Thoughts

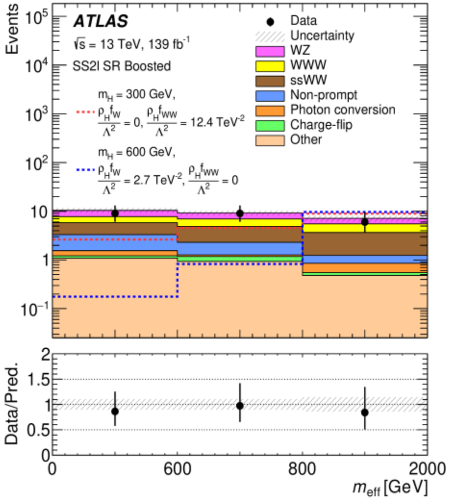
- Many interesting new Run-2 analyses searching for BSM scalars!
  - Please see Miaoran's and Rocky's talks
  - Wide variety of models, parameter space under exploration!
  - No direct evidence of new physics yet, but several hints of where to look in Run-3.
- Expected improved object identification, and reconstruction from major Run-2 upgrades (LAr Calorimeter, NSW, Trigger & DAQ)
- Novel analysis techniques continue to be developed
  - Combined with more data $\rightarrow$ ***expect improved search performance***
- **Thank you!**

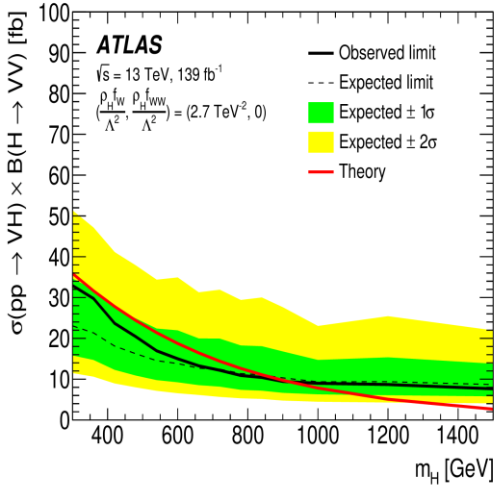
Backup

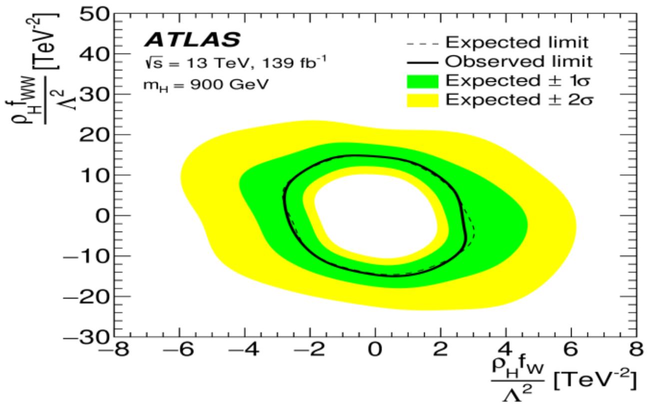
VH-Channel Generic Heavy Higgs Production

- Utilizes a separate boosted and resolved category.
- Applies a data-driven techniques to estimate fake and non-prompt lepton backgrounds.
- Effective mass (m_{eff}) defined as sum of pT and MET of all final-state objects

Selections	Boosted SR	Resolved SR	*ssWW* CR	Boosted *WZ* CR	Resolved *WZ* CR
Trigger	Single lepton				
Leptons	two same-sign leptons with $p_T > 27, 20$ GeV; zero additional veto leptons			three leptons with $p_T > 27, 20, 20$ GeV at least one SFOS lepton pair; zero additional veto leptons	
$m_{\ell\ell}$	> 100 GeV			-	
$m_{\ell\ell\ell}$	-			> 100 GeV	
b-jets	zero *b*-tagged small-*R* jets				
E_T^{miss}	> 80 GeV	> 60 GeV	> 40 GeV		
Large-*R* jets	at least one large-*R* jet with $p_T > 200$ GeV, $\|\eta\| < 2.0$ 50 GeV < m_J < 200 GeV and pass 80% *W*-tagger WP	zero large-*R* jets with $p_T > 200$ GeV, $\|\eta\| < 2.0$ 50 GeV < m_J < 200 GeV		at least one large-*R* jet with $p_T > 200$ GeV, $\|\eta\| < 2.0$ 50 GeV < m_J < 200 GeV	zero large-*R* jets with $p_T > 200$ GeV, $\|\eta\| < 2.0$ 50 GeV < m_J < 200 GeV
Small-*R* jets	-	at least two small-*R* jets with $p_T > 20$ GeV and $\|\eta\| < 2.5$		-	at least two small-*R* jets wi[th] $p_T > 20$ GeV and $\|\eta\| < 2.5$
m_{jj}	-	50 GeV < m_{jj} < 110 GeV	> 200 GeV	-	-

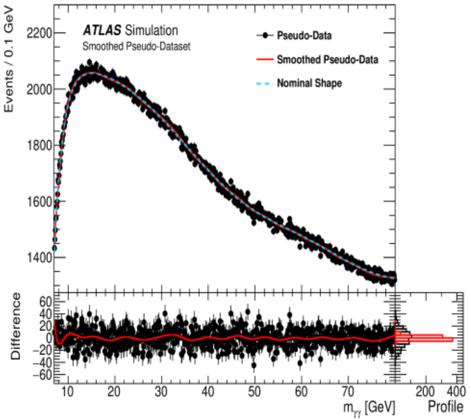






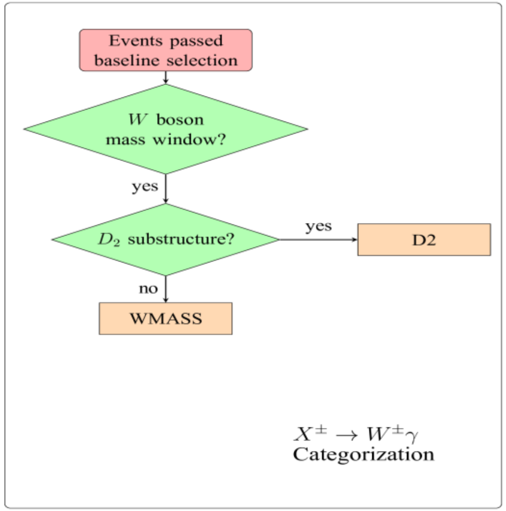
Boosted Di-photon Resonance Search

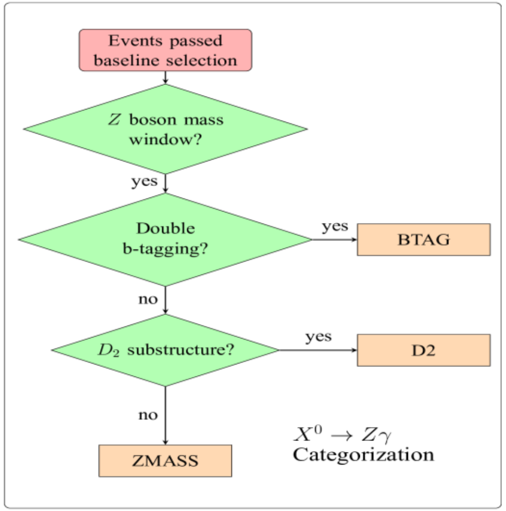
- Performs $m_{\gamma\gamma}$ fit using a double-sided Crystal Ball and analytic function (tuned to account for SS and applied GP-Reduction)
  - γj & jj contributions built from data CR's, $\gamma\gamma$ from MC
  - Less than (1%) differences of the fitted signal yield

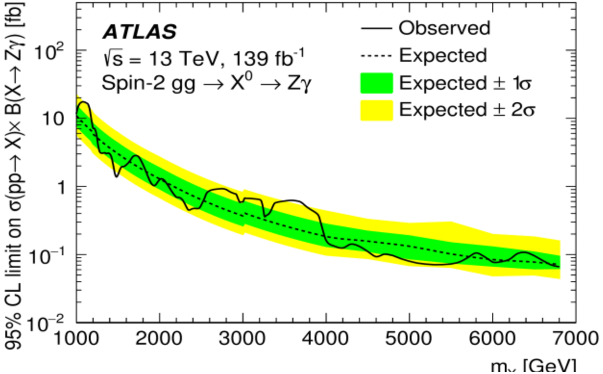


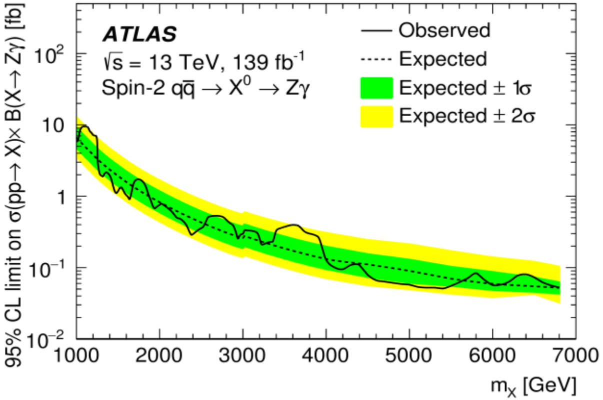
Source	Uncertainty
	On $\sigma_{\text{fid}} \cdot \mathcal{B}(X \to \gamma\gamma)$ [%]
Pile-up modelling	±3.5 (at 10 GeV) to ±2 (beyond 15 GeV), mass dependent
Photon energy resolution	±2.5 to ±2.7, mass dependent
Scale and PDFs uncertainties	±2.5 to ±0.5, mass dependent
Trigger on closely spaced photons	±2 (at 10 GeV) to <0.1 (beyond 35 GeV), mass dependent
Photon identification	±2.0
Isolation efficiency	±2.0
Luminosity (2015–2018)	±1.7
Trigger	±1.0
Signal shape modelling	<1
Photon energy scale	negligible
	Background modelling
Spurious signal (relative to δS)	30–65 events (10%–30%), mass dependent

High Mass $W\gamma/Z\gamma$ Resonances







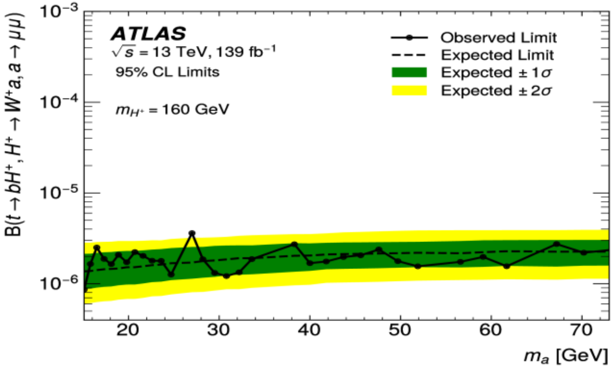


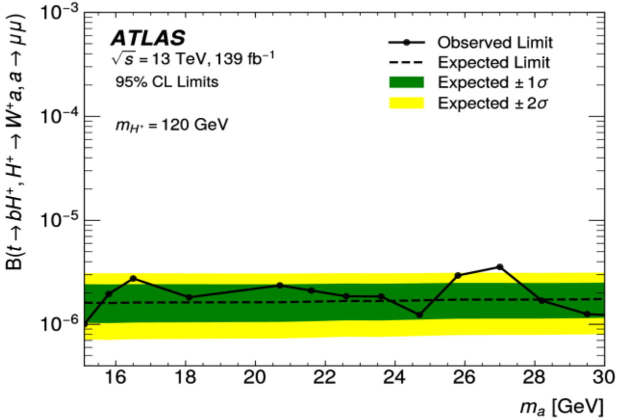
$$S(m_{J\gamma}; N, \mu, \sigma, \alpha_1, n_1, \alpha_2, n_2) = N \cdot \begin{cases} \left(\frac{n_1}{|\alpha_1|}\right)^{n_1} \exp\left(-\frac{|\alpha_1|^2}{2}\right) \left(\frac{n_1}{|\alpha_1|} - |\alpha_1| - \frac{m_{J\gamma}-\mu}{\sigma}\right)^{-n_1} & \frac{m_{J\gamma}-\mu}{\sigma} \le -\alpha_1 \\ \exp\left(-\frac{(m_{J\gamma}-\mu)^2}{2\sigma^2}\right) & -\alpha_1 < \frac{m_{J\gamma}-\mu}{\sigma} \le \alpha_2 \\ \left(\frac{n_2}{|\alpha_2|}\right)^{n_2} \exp\left(-\frac{|\alpha_2|^2}{2}\right) \left(\frac{n_2}{|\alpha_2|} - |\alpha_2| + \frac{m_{J\gamma}-\mu}{\sigma}\right)^{-n_2} & \alpha_2 < \frac{m_{J\gamma}-\mu}{\sigma}. \end{cases}$$

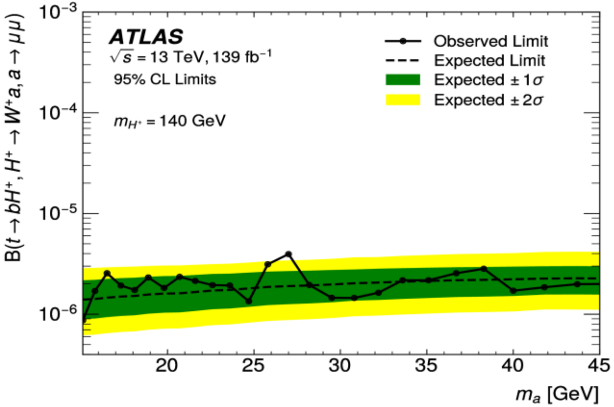
$$\mathcal{B}(m_{J\gamma}; p) = (1-x)^{p_1} x^{p_2 + p_3 \log(x)}$$

a→ $\mu\mu$ in Association w/ $t\bar{t}$

	Signal Regions		on-Z Control Region		$t\bar{t}$ Control Region
Channel	$e\mu\mu$	$\mu\mu\mu$	$e\mu\mu$	$\mu\mu\mu$	$e\mu\mu$
Binning	$m^{a}_{\mu\mu}$	$m^{a}_{\mu\mu}$	$n_{\text{jets}}, n_{b\text{-jets}}$	$n_{\text{jets}}, n_{b\text{-jets}}$	$p_{\text{T}}^{\mu,\text{fake}}$
$n_{\text{electrons}}$	1	0	1	0	1
n_{muons}	2	3	2	3	2
$m_{\mu\mu}$ [GeV]	$12 < m^{a}_{\mu\mu} < 77$	$12 < m^{a}_{\mu\mu} < 77$ and $m^{\text{other}}_{\mu\mu} < 77$ or > 107	$77 < m^{a}_{\mu\mu} < 107$	$77 < m^{a}_{\mu\mu} < 107$ or $77 < m^{\text{other}}_{\mu\mu} < 107$	$12 < m^{a}_{\mu\mu} < 77$
	-		-		-
n_{jets}	≥ 3				1 or 2
$n_{b\text{-jets}}$	≥ 1				1







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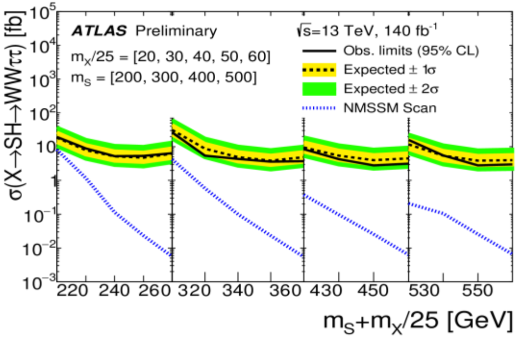
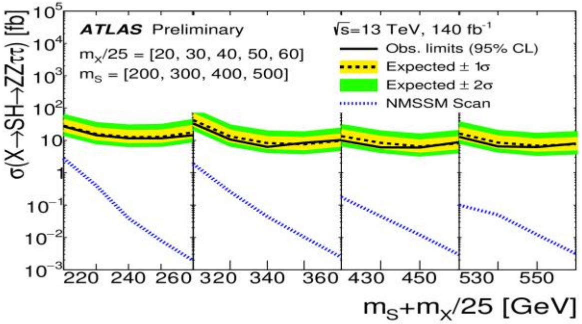
$X \rightarrow SH \rightarrow VV(\tau\tau)$

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

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





Light, Charged Higgs Production

N_b → / N_j ↓	**2b + 1bl:** exactly two *b*-tagged jets (60% OP) plus one loose *b*- tagged jet (70% OP)	**3b:** exactly three *b*-tagged jets (60% OP)	**≥4b:** at least four *b*-tagged jets (60% OP)
4j: exactly four jets	**4j, 2b + 1bl** (data-based $t\bar{t}$ corrections, 10 bins)	**4j, 3b** (signal region, 10 bins)	**4j, 4b** ($t\bar{t}+\geq$ 1b background control region and large *S/B* region, 1 bin)
5j: exactly five jets	**5j, 2b + 1bl** (data-based $t\bar{t}$ corrections, 10 bins)	**5j, 3b** (signal region, 10 bins)	**5j,≥ 4b** ($t\bar{t}+\geq$ 1b background control region and large *S/B* region, 1 bin)
6j: exactly six jets	**6j, 2b + 1bl** (data-based $t\bar{t}$ corrections, 10 bins)	**6j, 3b** (signal region, shape correction for the NN discriminant in low *S/B* bins, 10 bins)	**6j,≥ 4b** ($t\bar{t}+\geq$ 1b background control region, 1 bin)

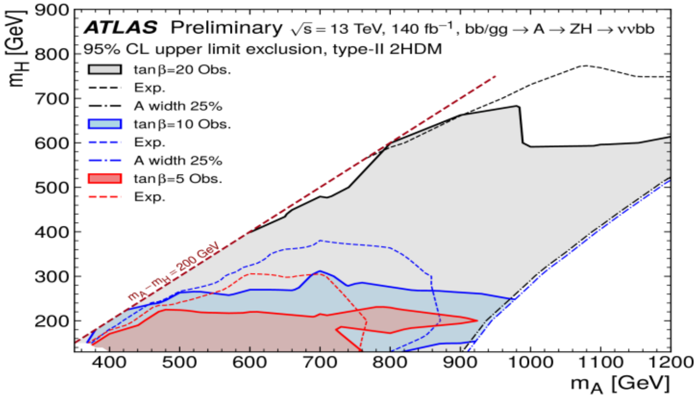
Regions used to derive $t\bar{t}$ correction **Regions for NN training and fit**

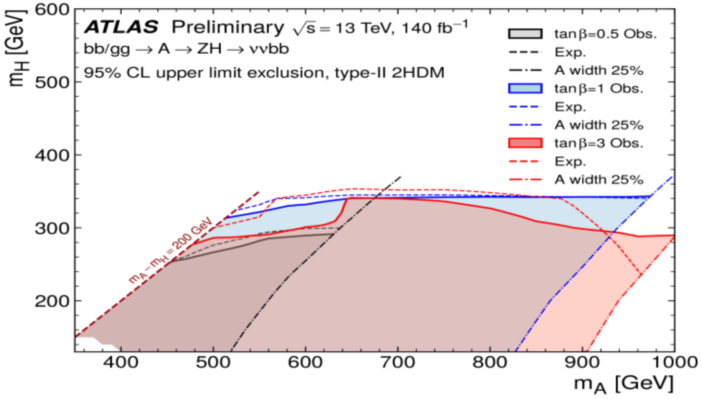
Input variables	Number of variables
p_T, η, and ϕ of the first six leading jets	18
b-tagging score of the fourth, fifth, and sixth jets	3
Lepton p_T, η, and ϕ	3
Missing transverse energy and its ϕ angle	2
Invariant mass between each of the three leading jets and the fourth jet	3
Total	29

(CP-odd) A→ZH (Heavy Higgs)

Cut	Regions				
	2L (CR)	$e\mu$ (CR)	1L (VR)	Hlo / Hhi (CR)	Hin (SR)
N jets	2-5				
N b-jets	> 2				
m_H^{cand}	> 50 GeV				
N hadronically decaying τ-leptons	0				
$p_T(V)$	> 150 GeV				
$\min_i \Delta\phi(\vec{E}_T^{\text{miss}}, \vec{p}_i^{\text{jet}})$	$> \pi/10$				
$\Delta R(b_1, b_2)$	< 3.3 (2 b-jets) < 3.5 (≥ 3 b-jets)				
N leptons	2		1	0	
Lepton flavour	$ee/\mu\mu$	$e\mu$	e/μ	-	
$p_T(\ell_1)$	> 27 GeV			-	
$\lvert m_Z^{\text{cand}} - m_Z \rvert$	< 10 GeV	-			
$\mathcal{S}_{\text{MET}}$	< 5	-	> 3	> 10	
$m_{\text{top}}^{\text{near}}$	-			> 180 GeV	
$m_{\text{top}}^{\text{far}}$	-			> 200 GeV	
$\lvert m_H^{\text{cand}} - m_H^{\text{hypo}} \rvert$	-			$> 0.2 \cdot m_H^{\text{hypo}}$	$< 0.2 \cdot m_H^{\text{hypo}}$

Cut		Regions				
		ss (CR)	L3hi_Zout (VR)	Hlo / Hhi (CR)	Hin (SR)	L3lo_Zin (VR)
N leptons		3				
$p_T(\ell_1)$		> 27 GeV				
N jets		≥ 4				
N b-jets		2				
$\lvert \eta_{H\text{-cand}}^{ZH\text{-r.fr.}} \rvert$		$< 2.2 + 0.0004 \cdot m_H^{\text{cand}} - 0.0011 \cdot m_A^{\text{cand}}$				
$p_T(\ell_3)$		> 13 GeV				> 7 GeV & < 13 GeV
Lepton flavour		$ee\mu/\mu\mu e$	$eee/ee\mu/\mu\mu e/\mu\mu\mu$			
OSSF lepton pairs		0	≥ 1			
$\lvert m_Z^{\text{cand}} - m_Z \rvert$		< 20 GeV	> 10 GeV & < 20 GeV	< 10 GeV		
$\lvert m_H^{\text{cand}} - m_H^{\text{hypo}} \rvert$	$m_H^{\text{hypo}} < 500$ GeV	-		$> 0.32 \cdot m_H^{\text{hypo}}$	$< 0.32 \cdot m_H^{\text{hypo}}$	-
	$m_H^{\text{hypo}} > 500$ GeV			$> 0.24 \cdot m_H^{\text{hypo}}$	$< 0.24 \cdot m_H^{\text{hypo}}$	





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