Searches for neutral heavy Higgs bosons decaying into a diboson system

Higgs2020

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On behalf of the ATLAS and CMS collaborations

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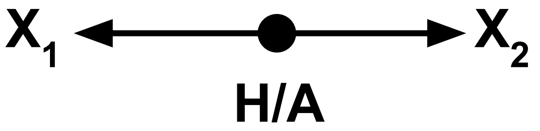
MAX-PLANCK-INSTITUT FÜR PHYSIK

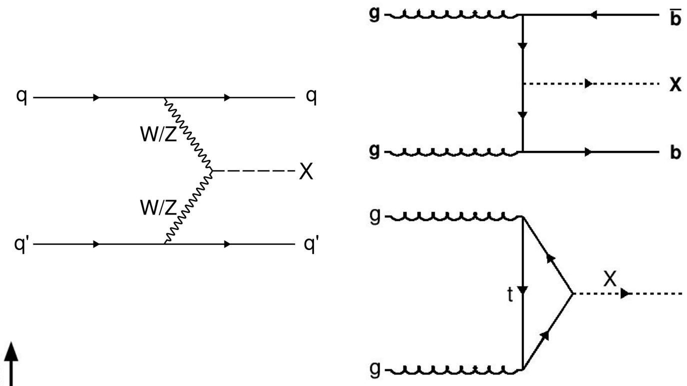
CMS

ATLAS EXPERIMENT

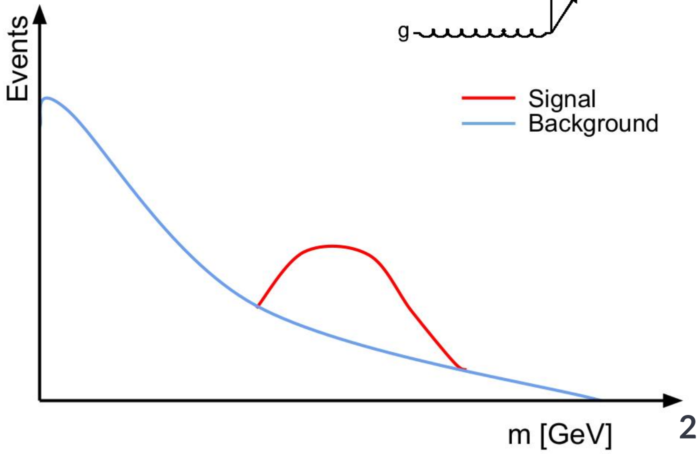
Introduction:



- **Focus: Searches for a heavy neutral Higgs boson H/A decaying into X_1 and X_2 (with $X_1/X_2 = \gamma$, Z, W, H, A, h)**
  - Searches are performed for different production modes
  - Targeting diverse sets of final states:
    - Multi-lepton
    - Di-photon
    - Di-tau
    - Lepton + jets
    - b-jets



- Most analyses are designed to perform (quasi) **model-independent searches for a bump in a smoothly falling mass spectrum**
  - **Interpretations in generic frameworks:**
    - **Extended Higgs sector:**
      - Two Higgs Doublet Model (2HDM)
      - Minimal Supersymmetric Standard Model (MSSM)
    - **Results also given in other frameworks:**
      - Heavy Vector Triplet (HVT) models
      - RS Extra-dimensional models



Searches for diboson resonances:

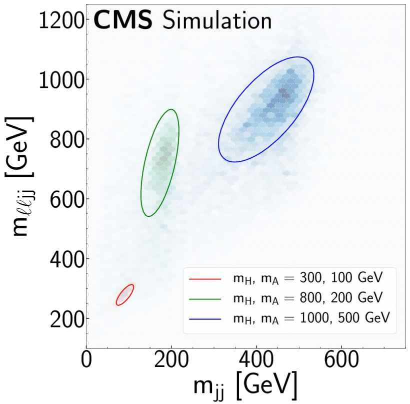
- **Analysis covered in detail in this presentation:**
  - Search for new neutral Higgs bosons decaying via H→ZA or A → ZH (CMS): *JHEP 03 (2020) 055*
  - Search for a heavy Higgs boson in A → ZH decays (ATLAS): HDBS-2018-13
  - Search for pseudo scalars in A → Zh decays (CMS): JHEP 03 (2020) 065
  - Search for pseudo scalars in A → Zh decays (ATLAS): ATLAS-CONF-2020-043
  - Search for a heavy Higgs boson decaying to γγ (ATLAS): ATLAS-CONF-2020-037
  - Search for a heavy Higgs boson decaying to WW (CMS): JHEP 03 (2020) 034
  - Search for a heavy Higgs boson decaying to ZZ (ATLAS): arXiv:2009.14791
- **Further analysis:**
  - Search for a spin-1 heavy resonance decaying to Zh (CMS): CMS-PAS-B2G-19-006
  - Search for a new scalar resonance decaying to ZZ (CMS): JHEP 06 (2018) 127
  - Search for hγ resonances (CMS): PRL 122 (2019) 081804
  - Search for hγ resonances (ATLAS): arXiv:2008.05928
  - Search for resonances decaying into Vh in fully hadronic final states (ATLAS): arXiv:2007.05293
  - Search for heavy resonances decaying to VV (ATLAS): arXiv:2004.14636
  - Search for high mass resonances decaying via X→ WW → lvlv (ATLAS): Eur. Phys. J. C 78 (2018) 24
  - Search for a dark Higgs boson decaying into WW or ZZ (ATLAS): arXiv:2010.06548

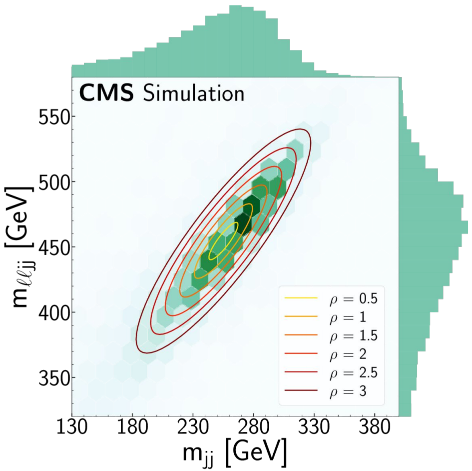
Search for new neutral Higgs bosons decaying via H→ZA or A → ZH:

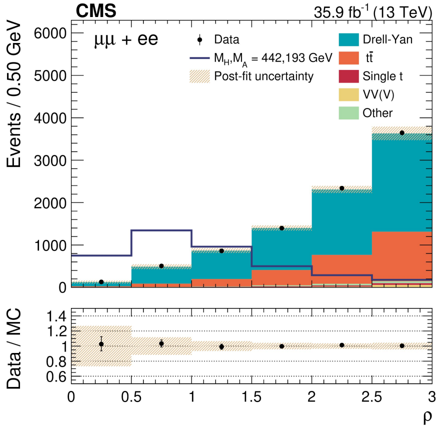
- **Probe ℓℓbb (ℓ = μ,e) final states**
- **Analysis strategy:**
  - Probe m_{jj} and $m_{\ell\ell bb}$ distributions for bumps within elliptical SRs
    - Size of ellipsoids depend on resonance masses (due to JER)
  - Transform 2D mass distribution into 1D distribution ρ:
    - Value of ρ depends on distance to the peak position of the 2D mass distribution
  - ML fit is performed using the distribution of ρ in ee + μμ SRs as well as in eμ + μe CRs as input
- **Dominant systematics:**
  - Modelling of the top quark, Z + jets and diboson backgrounds
    - In particular QCD scale uncertainties (~10%)

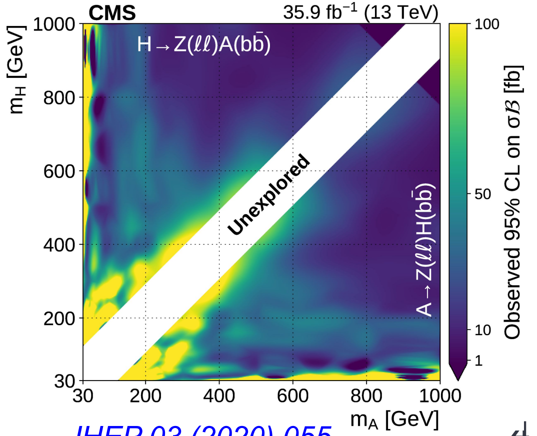
for m_H ≠ 125 GeV

Largest local (global) deviation wrt SM expectations was found to be 3.9σ (1.3 σ) for (m_A,m_H)=(630,160) GeV







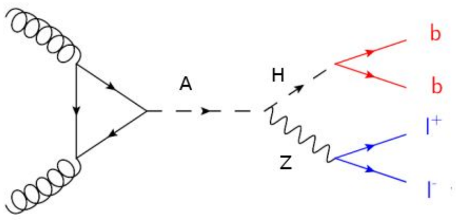


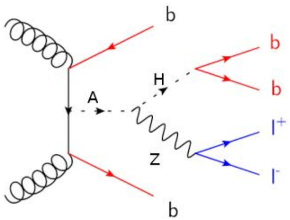
JHEP 03 (2020) 055

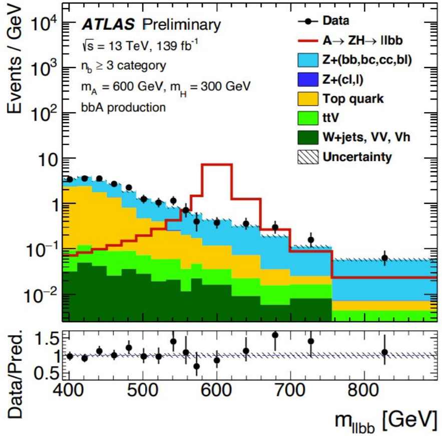
Search for a heavy Higgs boson in A → ZH decays:

Alan's slides:

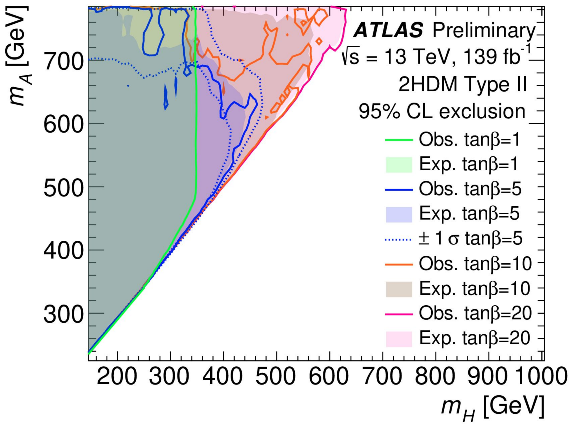
HDBS-2018-13







- **Search for a pseudo-scalar decaying via A → ZH (m_H>125 GeV)**
  - **Probe gg → A and bbA production modes**
  - **Consider H → bb (for gg → A and bbA) and H → WW (for gg → A) decays leading to ℓℓbb and ℓℓqqqq final states (with ℓ = μ,e)**

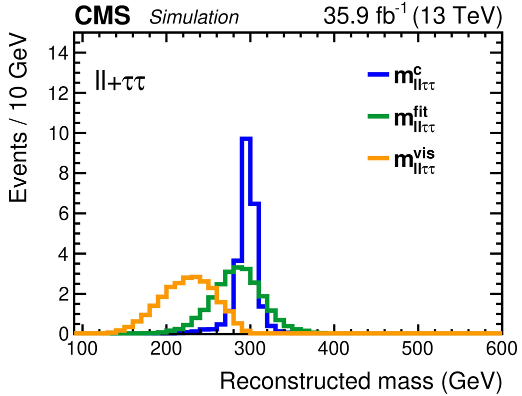


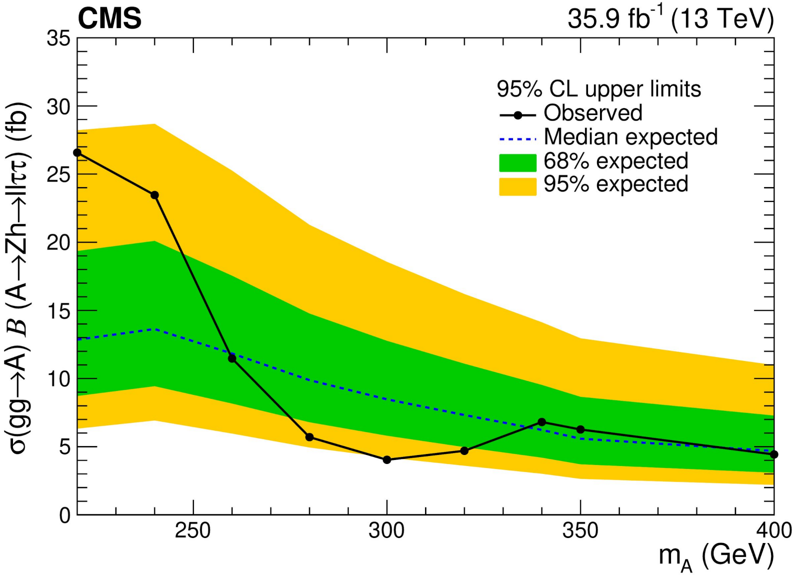
Largest local (global) deviation wrt SM expectations was found to be 3.1σ (1.3 σ) for (m_A,m_H)=(610,290) GeV

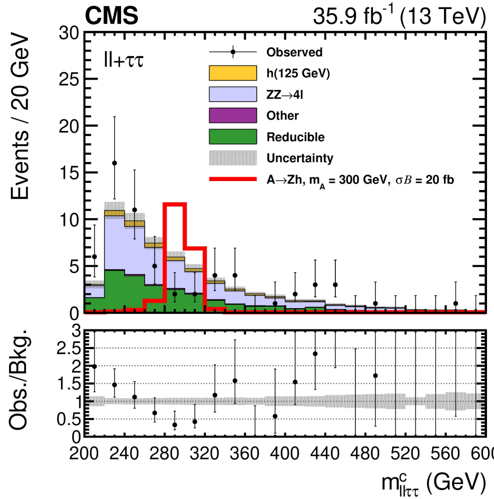
- **Analysis strategy:**
  - Signal parameterization:
    - ExpGaussExp (for ℓℓbb)
    - Double-Gaussian Crystal Ball (for ℓℓbbbb and ℓℓqqqq)
  - Fit m_A distribution in windows around m_H
- **Dominant Uncertainties:**
  - Data statistics (20% - 50%)
  - JES/JER (10%-30%)

Search for pseudo scalars in A → Zh decays:

- **Probe ℓℓττ (from ggA) and ℓℓττbb (from bbA) final states**
- **Analysis strategy:**
  - Reconstruct mass of pseudo scalar $\mathbf{m_{\ell\ell\tau\tau}}$ using the missing momentum vector and applying a constraint on the Higgs boson mass
  - Simultaneous fit of $m_{\ell\ell\tau\tau}$ distributions from the eight final states:
    - $\ell\ell + \tau_\ell \tau_\ell$, $\ell\ell + \tau_\ell \tau_h$, $\ell\ell + \tau_h \tau_h$ (with ℓ = e, μ and $\tau_\ell = \tau_e, \tau_\mu$)







- **Dominant systematics:**
  - Background modelling
    - ttV (~25%)
    - VVV (~25%)

for m_h = 125 GeV

JHEP 03 (2020) 065

Search for pseudo scalars in A → Zh decays:

- **Probe resolved and merged νν*bb* and ℓℓbb (ℓ = μ,e) final states**
- **Analysis strategy:**
  - Search for bumps in m_T or $m_{\ell\ell bb}$ spectra

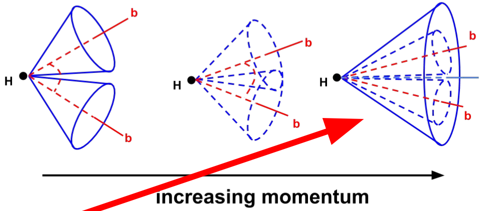
$$m_{\mathrm{T},Vh} = \sqrt{\left(E_{h,\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}}\right)^2 - \left(\vec{p}_{h,\mathrm{T}} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}}\right)^2}$$

- **Dominant uncertainties:**
  - Modelling of backgrounds (top bkg. ME +PS)
  - Large-R jets (mass resolution)

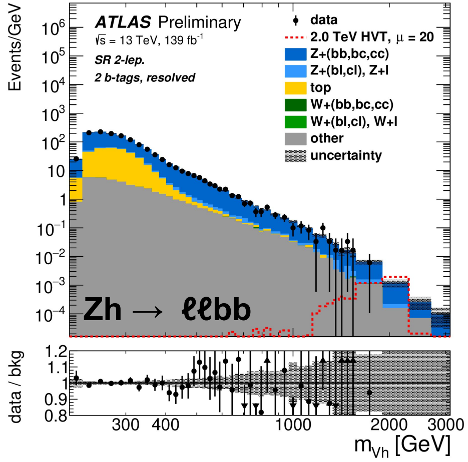
Resolved: use two small-R jets

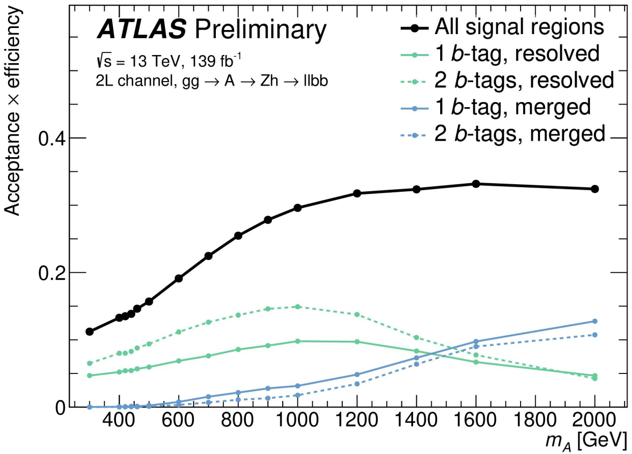
Merged: use a large-R jet to reconstruct Higgs bosons with around p_T > 250GeV

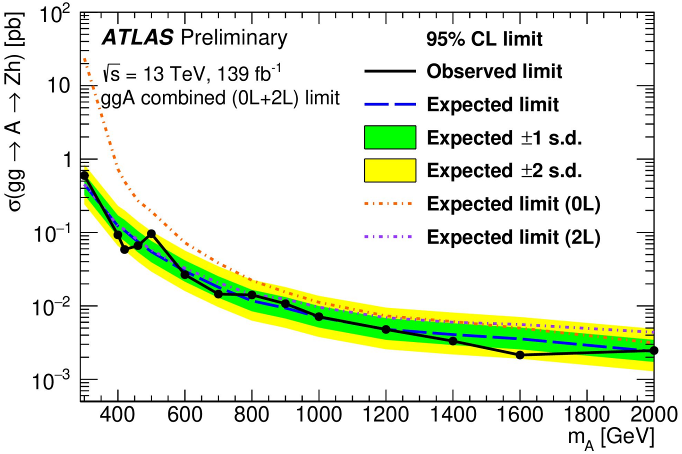
for m_h = 125 GeV



$$\Delta R \approx \frac{2m}{p_\mathrm{T}}$$







ATLAS-CONF-2020-043

Search for a heavy Higgs boson decaying to γγ:

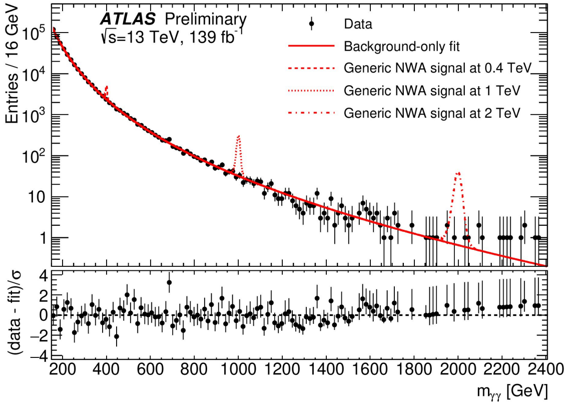
- **Search for spin-0 (and spin-2) γγ resonance in $m_{\gamma\gamma}$ spectrum**

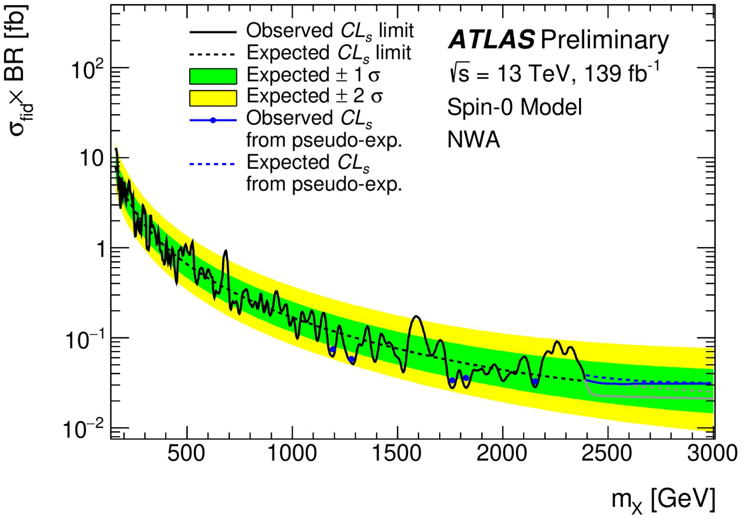
ATLAS-CONF-2020-037

- **Analysis strategy:**
  - Signal is modelled using a double-sided Crystal Ball function (for NW + LW) convolved with a relativistic Breit-Wigner (only for LW) form
  - Background (γγ, γj, jj) sum is estimated via fit to data:

$$f(x; b, a_0, a_1) = N(1 - x^{1/3})^b x^{a_0 + a_1 \log(x)} \quad \text{with} \quad x = m_{\gamma\gamma}/\sqrt{s}$$

- **Dominant uncertainties:**
  - Spurious signal estimation
  - Photon energy resolution

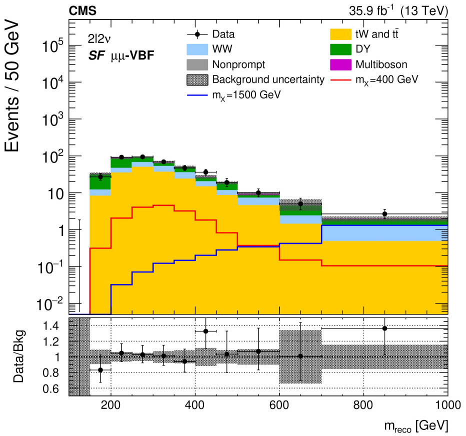


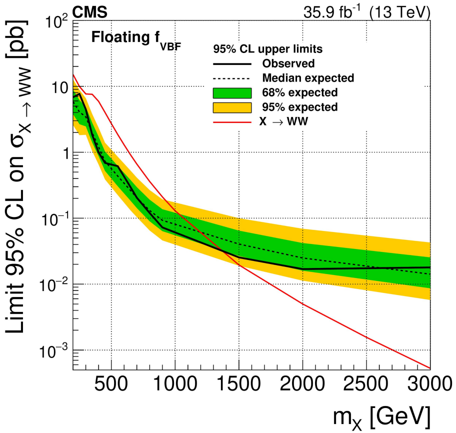


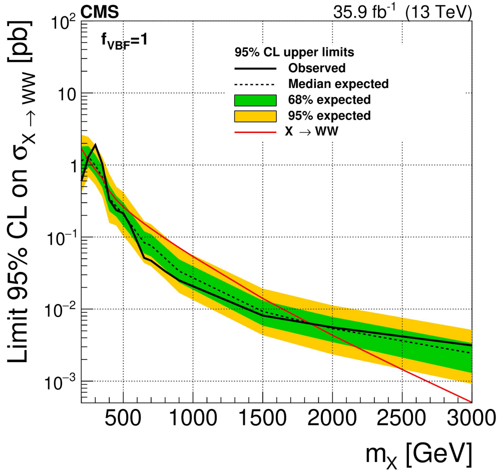
Largest local (global) deviation wrt SM expectations was found to be 3.3σ (1.3σ) for a mass around 680 GeV

Search for a heavy Higgs boson decaying to WW:

- **Probe ℓνℓν and (resolved/merged) ℓνqq final states (with ℓ = μ,e)**
- **Analysis strategy:**
  - Simultaneous fit to ggF and VBF production processes (for various f_{VBF} hypotheses)
    - Probe m_T and m_{lvqq} distributions
    - Consider zero-jet, one-jet, two-jet and VBF categories
    - Simultaneous fit of all mass distributions in the SRs, while CRs enter as single bins
      - Interference effects (between H, h and continuum) are taken into account
- **Dominant uncertainties:**
  - Jet bin migration effects
  - Modelling and normalisation of the WW background







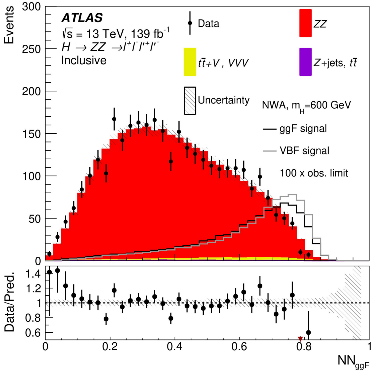
JHEP 03 (2020) 034

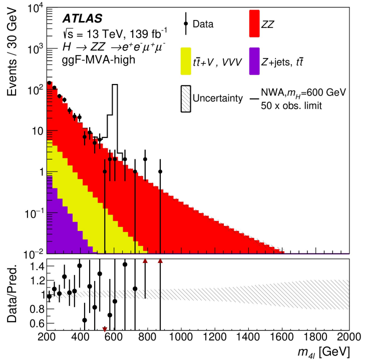
Search for a heavy Higgs boson decaying to ZZ:

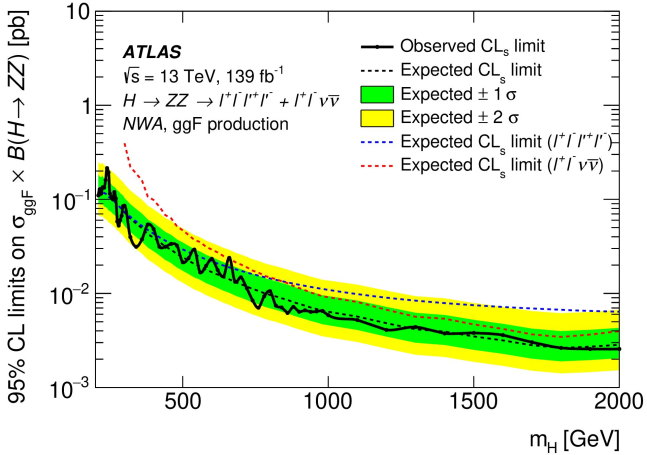
- **Probe ℓℓℓℓ and ℓℓνν final states (with ℓ = μ,e):**
  - Probe $m_{\ell\ell\ell\ell}$ and m_T spectra for signal hypotheses in range between 240 GeV and 2 TeV
- **Analysis strategy:**
  - Use two sets of neural networks (rNN + MLP) to classify 4ℓ events:
    - ggF: 4-vectors of leptons + kinematics of ℓℓℓℓ-system
    - VBF: 4-vectors of leptons and jets + ℓℓℓℓ-system
  - ℓℓνν events are classified via rectangular cuts
  - Fit ggF (VBF) contribution and floating VBF (ggF)
    - Combined fit using $m_{\ell\ell\ell\ell}$ and m_T distributions
    - Interference effects (between H, h and continuum) are taken into account
- **Dominant systematics:**
  - Systematics are negligible wrt statistical uncertainty (~50%)

arXiv:2009.14791

$$m_T \equiv \sqrt{\left[\sqrt{m_Z^2 + \left(p_T^{\ell\ell}\right)^2} + \sqrt{m_Z^2 + \left(E_T^{\text{miss}}\right)^2}\right]^2 - \left|\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{\text{miss}}\right|^2}$$

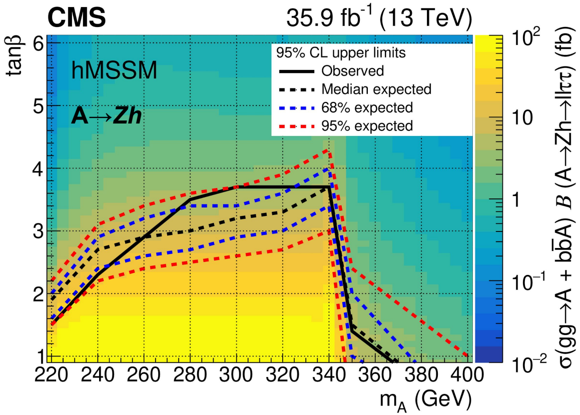


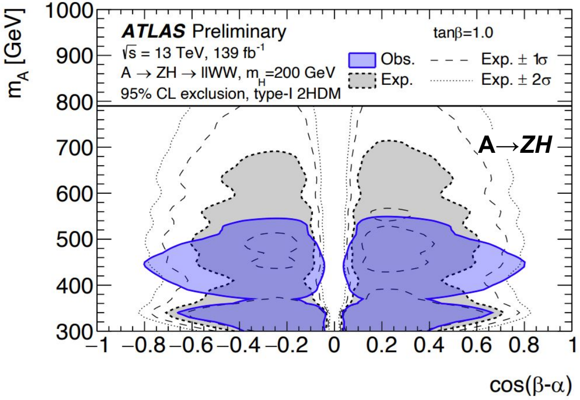


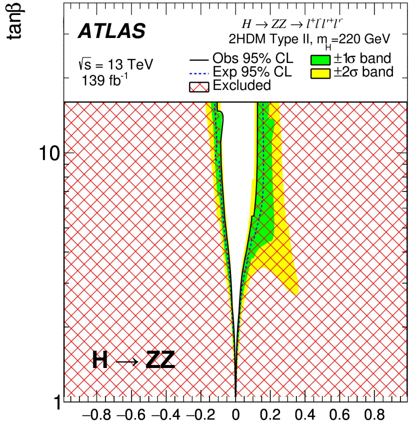


Interpretations:

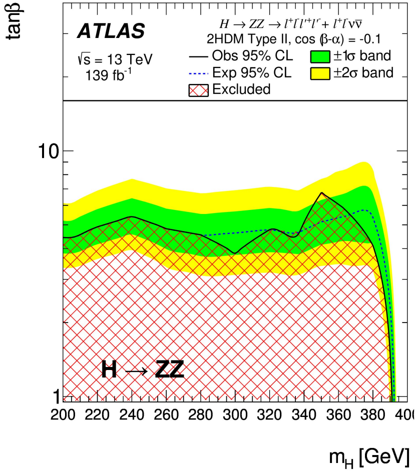
- **Model independent limits are re-interpreted in the context of the 2HDM as well as the hMSSM** (and other MSSM scenarios)

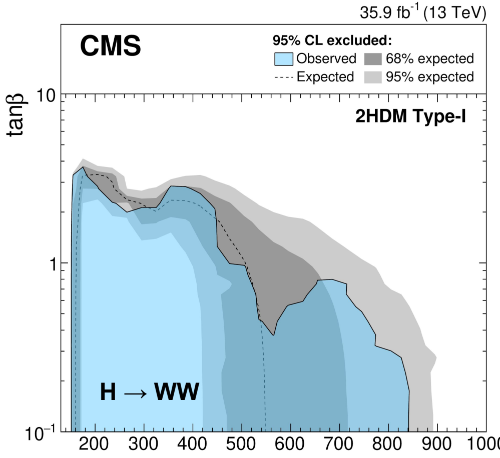




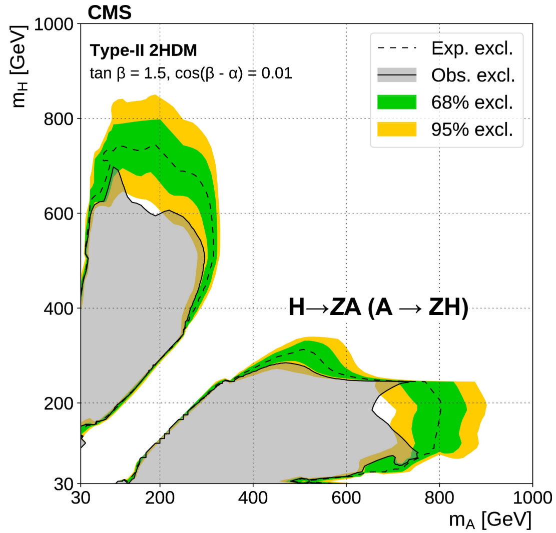


[arXiv:2009.14791](https://arxiv.org/abs/2009.14791) cos(β-α)





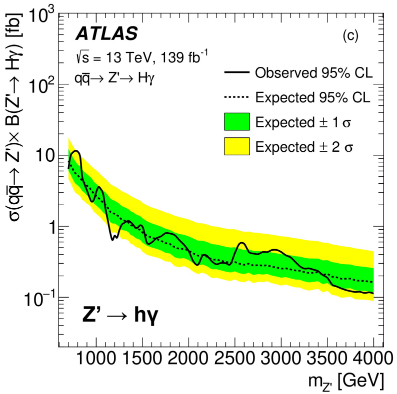
[JHEP 03 (2020) 034](https://doi.org/10.1007/JHEP03(2020)034)

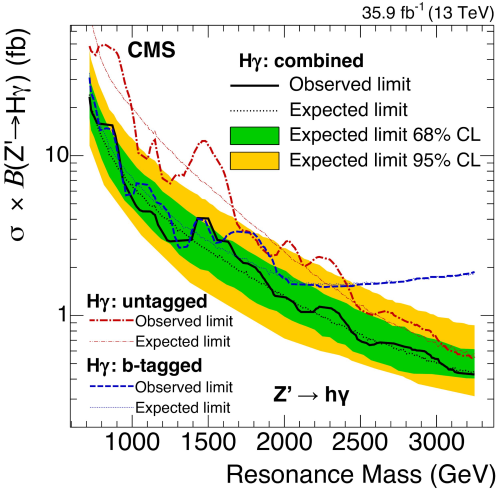


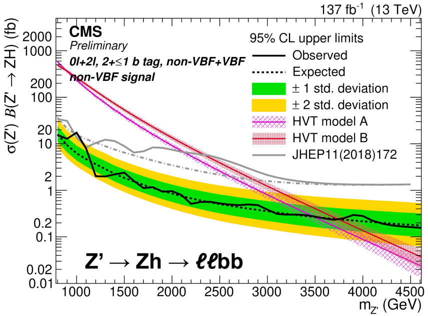
[JHEP 03 (2020) 055](https://doi.org/10.1007/JHEP03(2020)055)

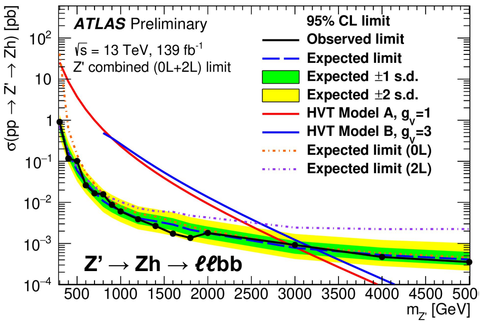
Further results:

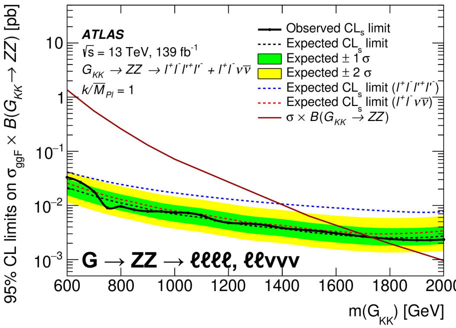
- **Many analyses in ATLAS and CMS that target resonances decaying into two bosons also study alternative/additional spin hypotheses**

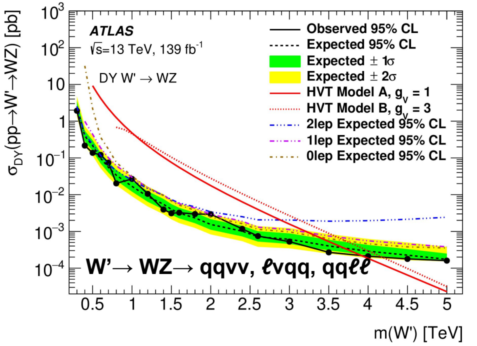


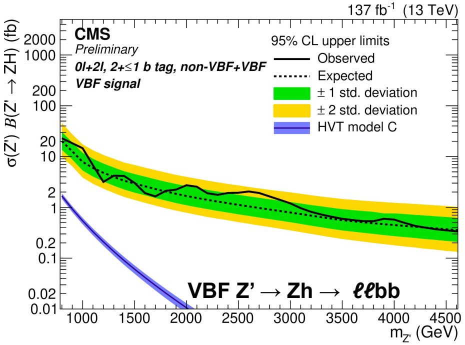


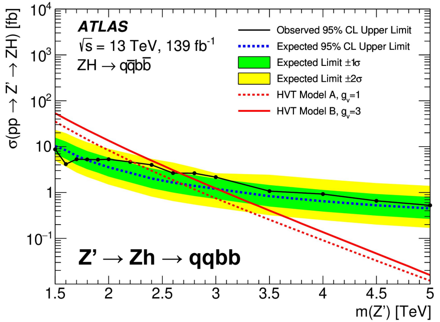


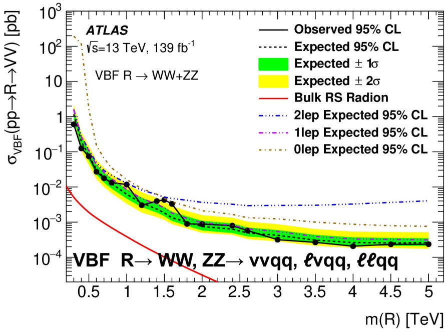










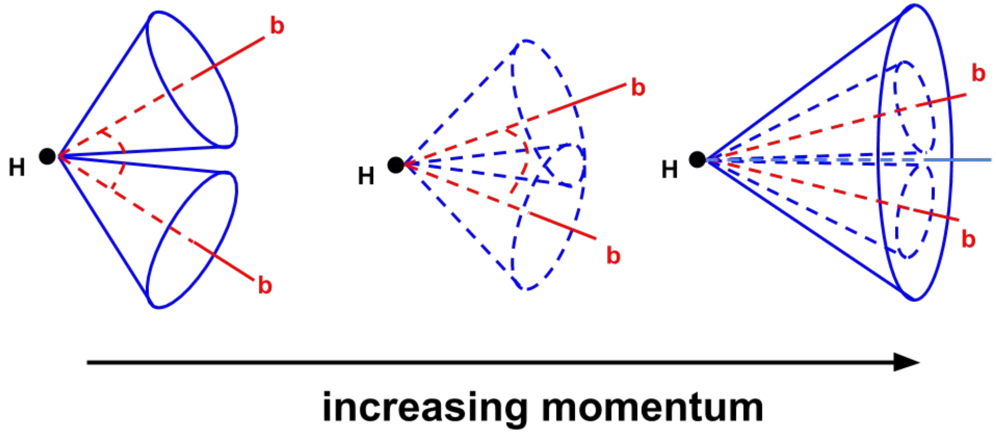


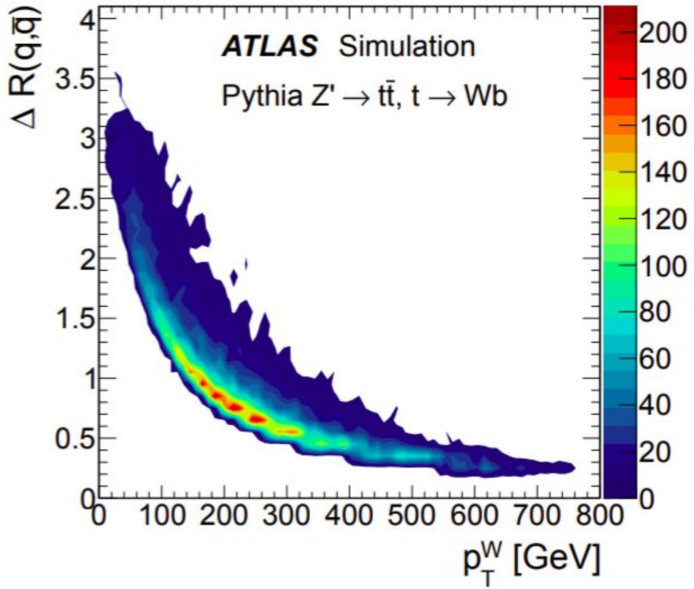
Concluding remarks

- **Many interesting searches for neutral heavy Higgs bosons (and other resonances) are ongoing within ATLAS and CMS**
  - Presented only a few highlights of available results.
    - Additional results can be found via the ATLAS and CMS publication pages
  - No significant hint for physics beyond the SM has been observed so far
  - Many results based on the full Run-2 data set are expected in the next month/years

back-up

Boosted topologies:





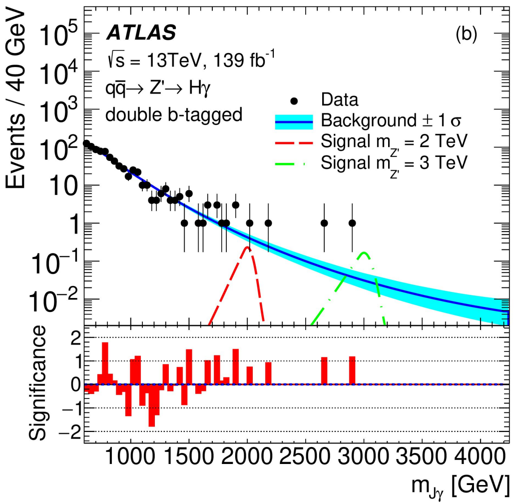
- **Decay products of boosted particles tend to be collimated**
- For p_T^{top} > 450GeV and p_T^{Higgs} > 300GeV decay products tend to have an angular separation smaller than 0.8
  - Partonic structure of decays can no longer be sufficiently described by R=0.4 jets
    - Use R=1.0 jets instead

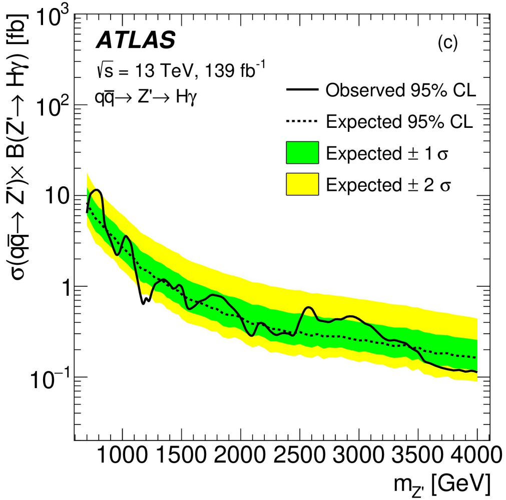
$$\Delta R \approx \frac{2m}{p_T}$$

Search for hγ resonances:

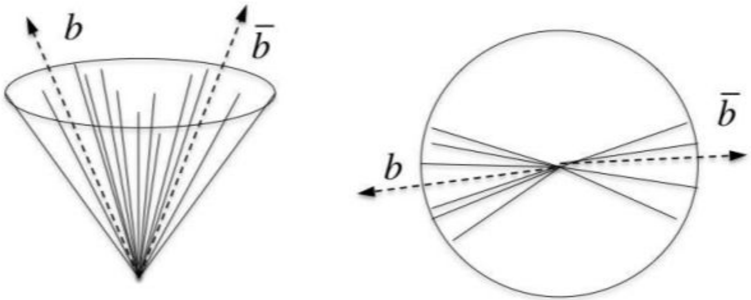
- **Search for hγ resonances in merged bbγ final state**
  - Hunt for bump in $m_{bb\gamma}$ spectrum covering mass range between 0.7 and 4 TeV
    - Use parametric fit function to describe background (smoothly falling)
    - The signal is modeled as a sum of a Crystal Ball function and a Gaussian
    - Use generic spin 1 (qq → Z' → hγ) interpretation
  - **Use CoM tagging (separate 1-tag and 2-tag categories)**
- **Dominant uncertainties:**
  - Large-R jet (mass)

arXiv:2008.05928





Boost large-R jet constituents into Center of Mass (CoM) frame to disentangle decay products



arXiv:1507.06913

Search for a heavy Higgs boson in A → ZH decays:

Table 2: Summary of the event selection for signal and control regions in the $A \to ZH \to \ell\ell WW$ channel.

Single-electron or single-muon trigger	
Exactly 2 leptons (e or μ) ($p_{\mathrm{T}} > 15$ GeV) with the leading one having $p_{\mathrm{T}} > 30$ GeV	
Opposite electric charge for $\mu\mu$ pairs; 80 GeV $< m_{\ell\ell,\, e\mu} <$ 100 GeV, $\ell = e,\ \mu$	
At least 4 jets ($p_{\mathrm{T}} > 20$ GeV) with leading and second leading jets having $p_{\mathrm{T}} > 40,\ 30$ GeV	
Jets chosen with a cut-based selection	
$\sqrt{\Sigma p_{\mathrm{T}}^2}/m_{2\ell 4q} > 0.3$	
Signal region	ee or $\mu\mu$ pair $m_H - 53$ GeV $< m_{4q} < 0.97 \cdot m_H + 54$ GeV
Z+jets control region	ee or $\mu\mu$ pair $m_{4q} < m_H - 53$ GeV or $m_{4q} > 0.97 \cdot m_H + 54$ GeV
Top control region	$e\mu$ pair $m_H - 53$ GeV $< m_{4q} < 0.97 \cdot m_H + 54$ GeV

ANA-HDBS-2018-13

Search for a heavy Higgs boson in A → ZH decays:

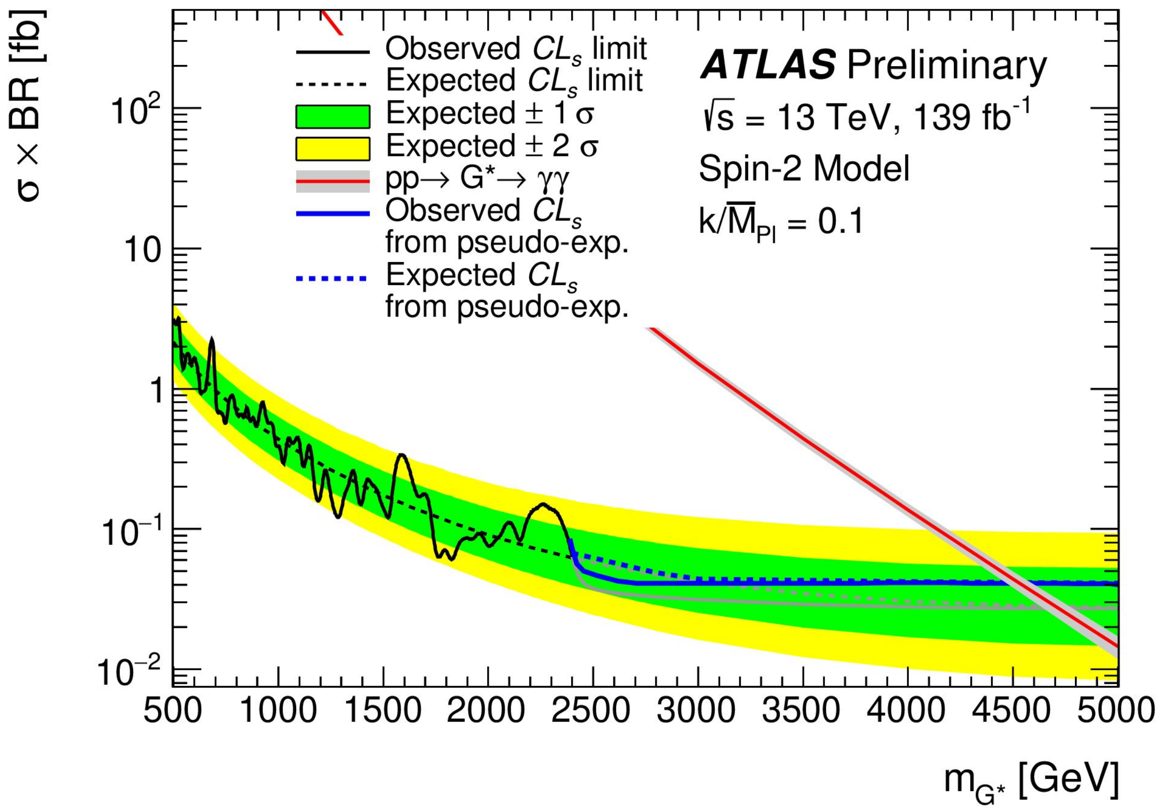
Table 3: The effect of the most important sources of uncertainty on the signal-strength parameter at two example mass points of $(m_A,\ m_H) = (230,\ 130)$ GeV and $(m_A,\ m_H) = (700,\ 200)$ GeV in the $\ell\ell bb$ channel, for both the gluon–gluon fusion and b-associated production of a narrow-width A boson. The signal cross sections are taken to be the expected median upper limits (see Section 8) and they correspond to values that are shown on the table next to the indicated mass points. JES and JER stand for jet energy scale and jet energy resolution, 'Sim. stat.' for simulation statistics, 'Sig. interp.' for signal interpolation, and 'Bkg. model.' for the background modelling. 'Theory' refers to theoretical uncertainties due to PDF choice, factorisation and renormalisation scales, and initial- and final-state radiation.

$A \to ZH \to \ell\ell bb$							
Gluon–gluon fusion production				b-associated production			
(230, 130) GeV, 0.31 pb		(700, 200) GeV, 0.017 pb		(230, 130) GeV, 0.16 pb		(700, 200) GeV, 0.018 pb	
Source	$\Delta\mu/\mu$ [%]	Source	$\Delta\mu/\mu$ [%]	Source	$\Delta\mu/\mu$ [%]	Source	$\Delta\mu/\mu$ [%]
Data stat.	28	Data stat.	45	Data stat.	33	Data stat.	46
Total syst.	36	Total syst.	26	Total syst.	33	Total syst.	25
Sim. stat.	19	Sim. stat.	7.2	Sim. stat.	18	Sim. stat.	7.2
Sig. interp.	9.9	Sig. interp.	8.7	Sig. interp.	13	Sig. interp	13
Bkg. model.	19	Bkg. model.	18	Bkg. model.	15	Bkg. model.	16
JES/JER	20	JES/JER	18	JES/JER	14	JES/JER	16
b-tagging	7.5	b-tagging	12	b-tagging	9.5	b-tagging	12
Theory	7.4	Theory	9.5	Theory	5.0	Theory	7.1

ANA-HDBS-2018-13

Search for a heavy Higgs boson decaying to γγ:

Limits on alternative, Spin-2, hypothesis in the context of a warped extra-dimension benchmark model



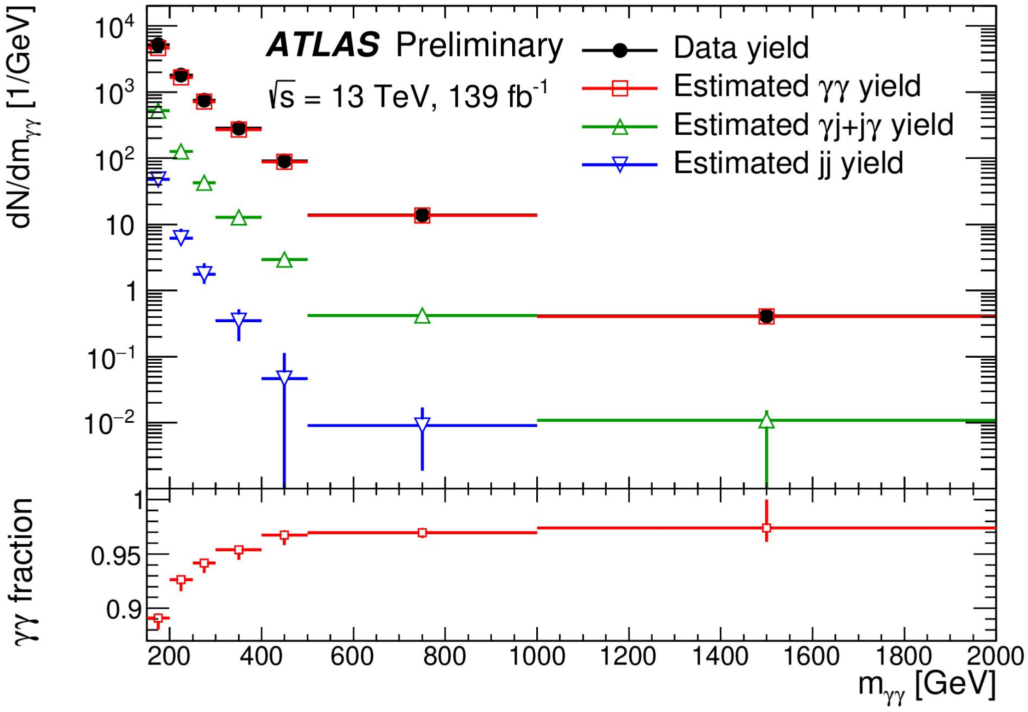
Observed upper limits on the fiducial and the total production cross-section times branching ratio

	Spin-0	
m_X	400 GeV	2800 GeV
NWA	1.1 fb	0.03 fb
Γ_X/m_X= 2%	2.5 fb	0.03 fb
Γ_X/m_X= 6%	4.4 fb	0.03 fb
Γ_X/m_X= 10%	8.3 fb	0.03 fb
	Spin-2	
m_{G^*}	500 GeV	5000 GeV
$k/\overline{M}_{\mathrm{Pl}}$= 0.01	1.9 fb	0.04 fb
$k/\overline{M}_{\mathrm{Pl}}$= 0.05	2.3 fb	0.04 fb
$k/\overline{M}_{\mathrm{Pl}}$= 0.1	3.2 fb	0.04 fb

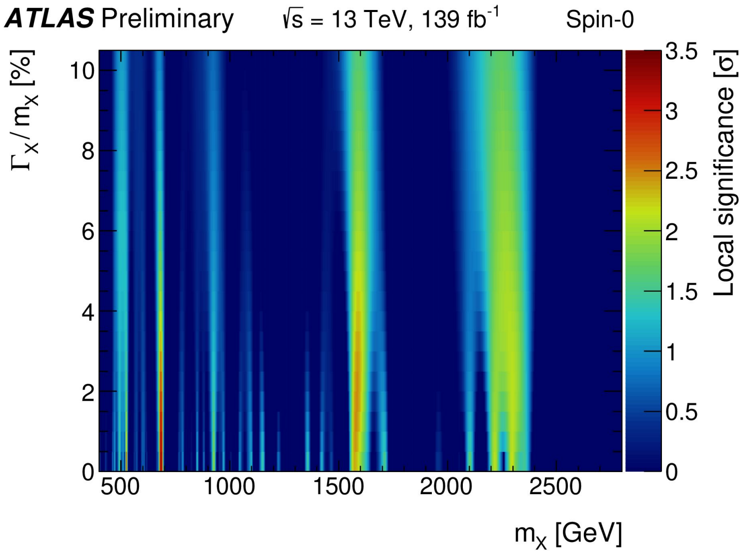
ATLAS-CONF-2020-037

Search for a heavy Higgs boson decaying to γγ:

Background composition as a function of the di-photon mass

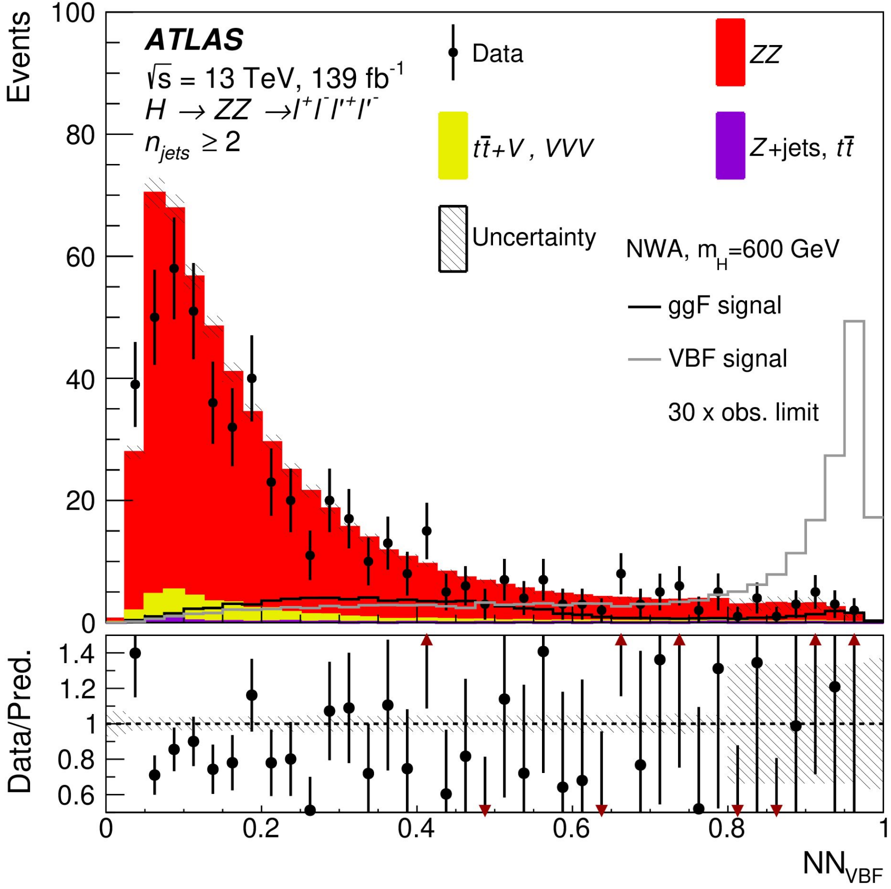


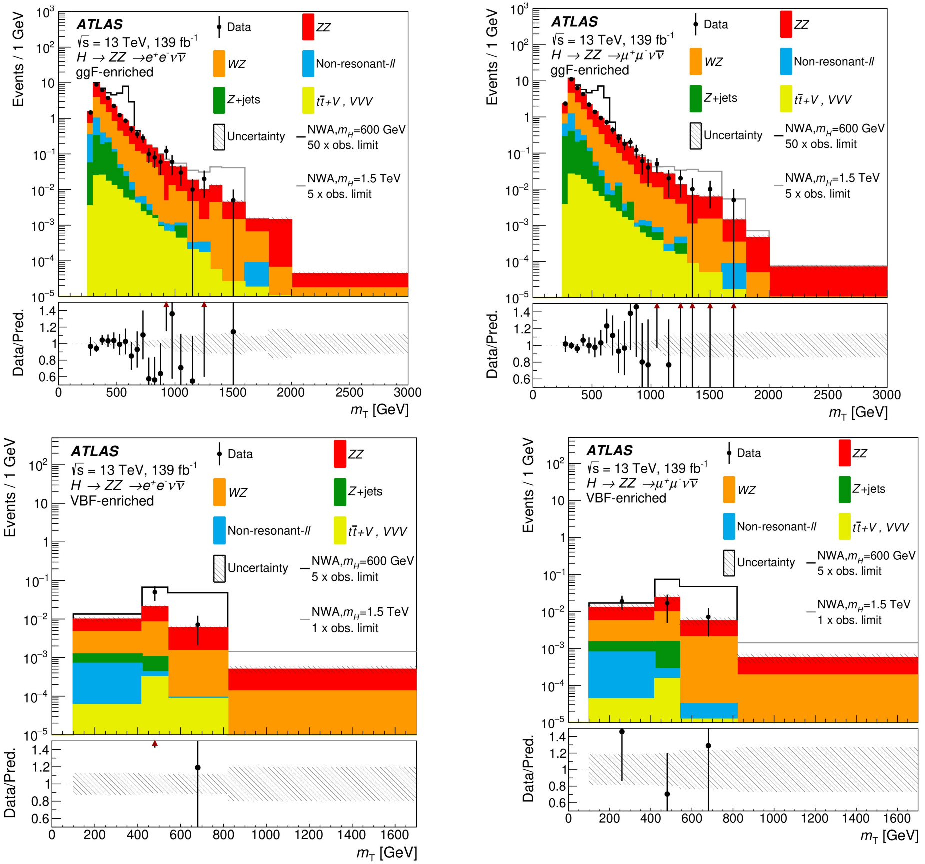
Compatibility, in terms of local p_0 quantified in standard deviations σ, with the background-only hypothesis as a function of the assumed signal mass m_X and relative width Γ_X/m_X for the spin-0 resonance search



ATLAS-CONF-2020-037

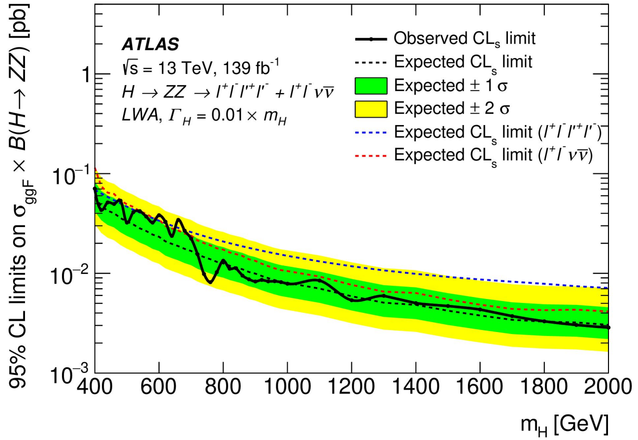
Search for a heavy Higgs boson decaying to ZZ:

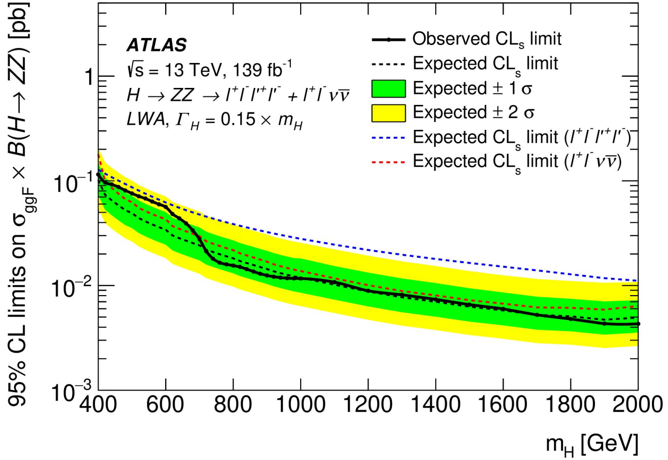


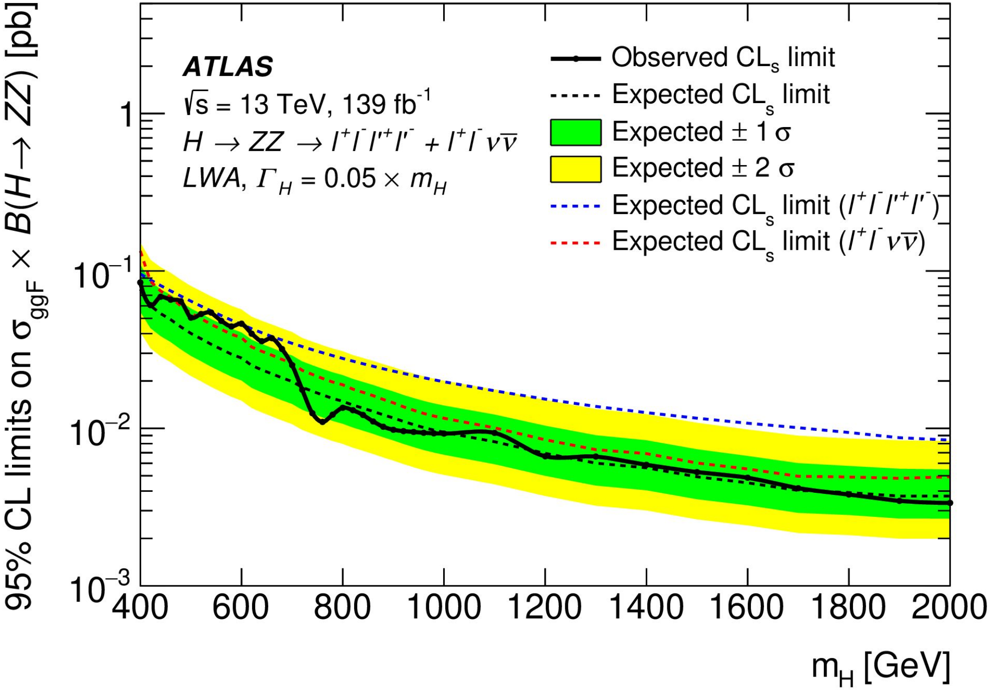


[arXiv:2009.14791](https://arxiv.org/abs/2009.14791)

Search for a heavy Higgs boson decaying to ZZ:







arXiv:2009.14791

Search for a heavy Higgs boson decaying to ZZ:

Input features used in the `VBF-classifier' for the $\ell\ell\ell\ell$ analysis. The rNN stands for the recurrent neural network and MLP for the multilayer perceptron.

Model	Inputs	Description
rNN	$p_{\mathrm{T}}^{\mathrm{j0}}, p_{\mathrm{T}}^{\mathrm{j1}}$	transverse momenta of the two leading jets
	$\eta^{\mathrm{j0}}, \eta^{\mathrm{j1}}$	pseudorapidity of the two leading jets
	$p_{\mathrm{T}}^{\ell 0}, p_{\mathrm{T}}^{\ell 1}, p_{\mathrm{T}}^{\ell 2}, p_{\mathrm{T}}^{\ell 3}$	transverse momenta of the four leptons
	$\eta^{\ell 0}, \eta^{\ell 1}, \eta^{\ell 2}, \eta^{\ell 3}$	pseudorapidity of the four leptons
MLP	$m_{4\ell}$	invariant mass of the four-lepton system
	m_{jj}	invariant mass of the two-leading-jet system
	$p_{\mathrm{T}}^{\mathrm{jj}}$	transverse momentum of the two-leading-jet system
	$\Delta\eta_{\mathrm{H,j}}$	difference in pseudorapidity between the four-lepton system and the leading jet
	$\min\Delta R_{\mathrm{jZ}}$	minimum distance between one of the two lepton pairs and a jet

arXiv:2009.14791

Search for a heavy Higgs boson decaying to ZZ:

Model	Inputs	Description
rNN	$p_T^{\ell 0}, p_T^{\ell 1}, p_T^{\ell 2}, p_T^{\ell 3}$	transverse momenta of the four leptons
	$\eta^{\ell 0}, \eta^{\ell 1}, \eta^{\ell 2}, \eta^{\ell 3}$	pseudorapidity of the four leptons
MLP	$m_{4\ell}$	invariant mass of the four-lepton system
	$p_T^{4\ell}$	transverse momentum of the four-lepton system
	$\eta^{4\ell}$	pseudorapidity of the four-lepton system
	$\cos\theta^*$	production angle of the leading Z defined in the four-lepton rest frame
	$\cos\theta_1$	angle between the negative final state lepton and the direction of flight of leading Z in the Z rest frame
	$\cos\theta_2$	angle between the negative final state lepton and the direction of flight of sub-leading Z in the Z rest frame
	Φ	angle between the decay planes of the four final state leptons expressed in the four-lepton rest frame
	p_T^{j0}	transverse momentum of the leading jet
	η^{j0}	pseudorapidity of the leading jet

Input features used in the `ggF-classifier' for the $\ell\ell\ell\ell$ analysis. The rNN stands for the recurrent neural network and MLP for the multilayer perceptron.

arXiv:2009.14791

Search for a heavy Higgs boson decaying to WW:

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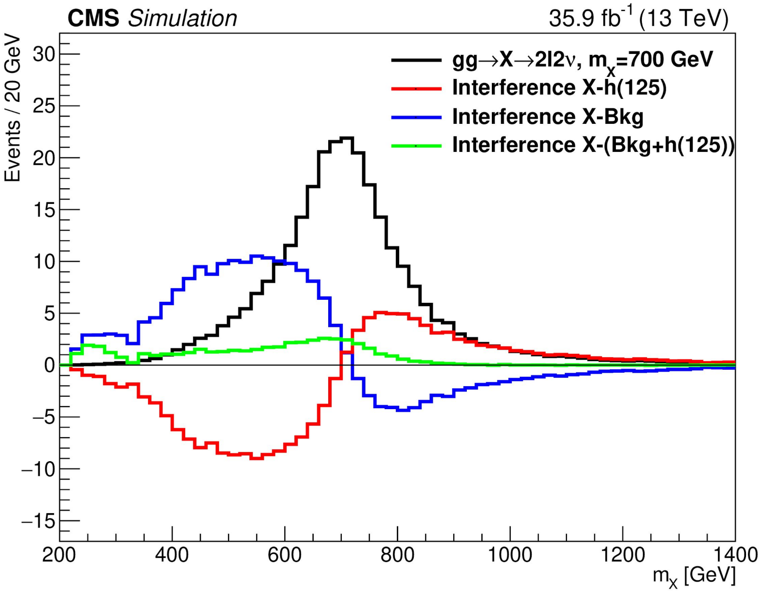
Generator-level mass of a ggF-produced 700 GeV signal normalized to the SM cross section. The effects of the interference of the signal with the gg→WW continuum and the gg→h(125) off-shell tail are shown, together with the total interference effect.

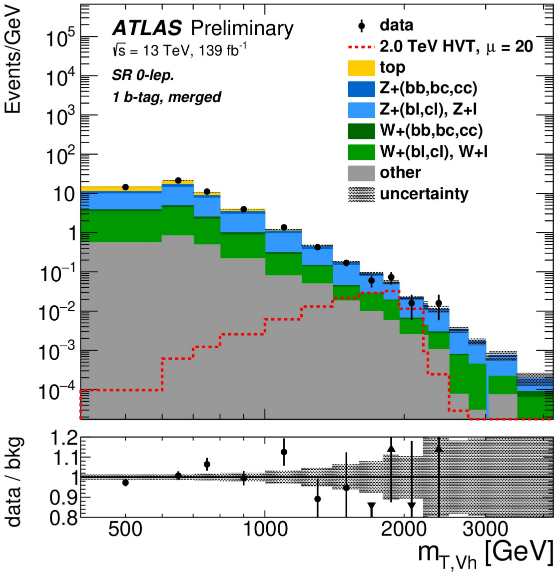


Source of uncertainty	$X \to WW \to 2\ell 2\nu$	$X \to WW \to \ell\nu 2q$ Resolved	$X \to WW \to \ell\nu 2q$ Boosted
Experimental sources			
Integrated luminosity	2.5%	2.5%	2.5%
Lepton trigger*	2%	1%	1%
Lepton reconstruction & ident.*	1–3%	1–2%	1–2%
Electron energy scale*	0.1–1%	0.2–1%	0.1–1%
Muon momentum scale*	0.1–1%	0.1–1%	0.1–1%
Jet energy scale*	1–10%	1–6%	1–3%
Jet energy resolution*	—	0.5–2%	0.3–1%
p_T^{miss} *	0.1–1%	1–3%	0.1–1%
b tagging/mistag*	0.1–5%	0.1–1%	0.1–1%
W tagging (τ_{21})	—	—	6%
W tagging (extrapolation)	—	—	1–13%
W m_J scale	—	—	0.1–1%
W m_J resolution	—	—	2–5%
Background estimates			
WW	6–45%	10%	10%
top quark	3–5%	7–9%	8–10%
W+jets	30%	5–11%	4–20%
QCD multijet	—	10%	10%
DY	5–20%	10%	10%
Theoretical sources			
PDF and α_S (acceptance)*	1–4%	1–4%	1–7%
Renorm./factor. scales (acceptance)*	1–6%	1–18%	1–18%
PDF and α_S (σ_X)	2–16%	2–4%	2–16%
Renorm./factor. scales (σ_X)	0.2–9%	0.2–4%	0.2–9%
Jet multiplicity categorization ($\sigma_{gg\to X}$)*	5–20%	—	—
WW p_T^{WW} reweighting*	3–10%	—	—
WW UE & PS	5–10%	—	—
DY p_T^{miss} reweighting*	0.2–1%	—	—

Search for pseudo scalars in A → Zh decays:

Topological and kinematic selections for each channel and category as described in the text. The various signal regions are divided into ``1 b-tag" or ``2 b-tags" categories depending on the multiplicity of b-tagged jets in the event.

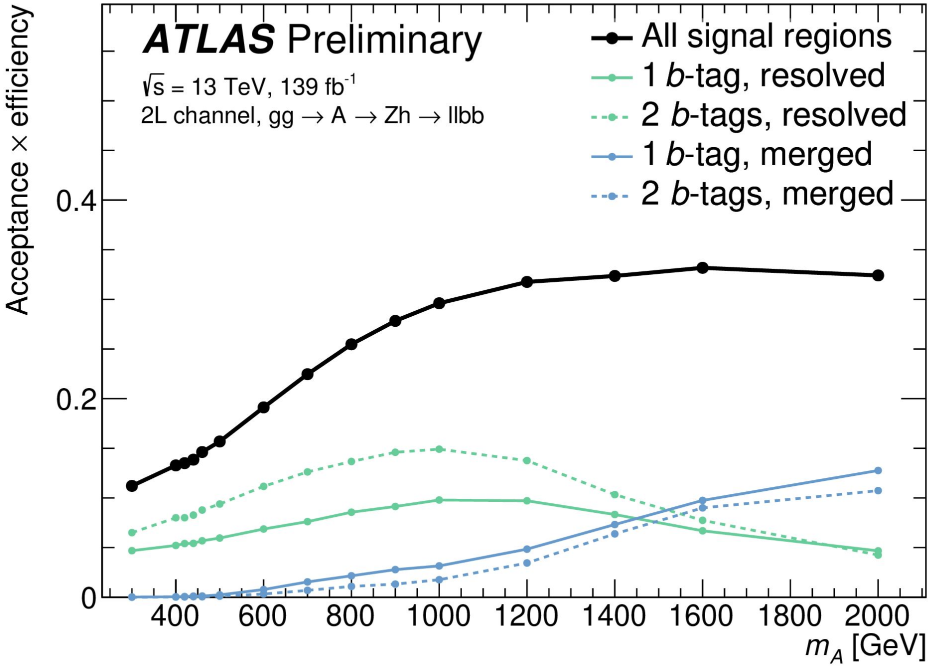
Variable	Resolved	Merged
	Common selection	
Number of jets	≥2 central Small-R jets (0, 2-lep.)	≥1 large-R jet ≥ 2 VR track jets (matched to leading large-R jet)
Leading jet p_{T} [GeV]	> 45	> 250
m_{jj} [GeV]	110–140 (0-lep.), 100–145 (2-lep.)	75–145
	0-lepton selection	
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 150	> 200
H_{T} [GeV]	> 150 (120^{*})	–
$\Delta\phi_{bb}$	$< 7\pi/9$	–
$p_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 60	
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{~miss}})$	$< \pi/2$	
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, h)$	$> 2\pi/3$	
$\min\left[\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \text{Small-}R\text{ jet})\right]$	$> \pi/9$ (2 or 3 jets), $> \pi/6$ (≥ 4 jets)	
$N_{\tau_{\mathrm{had}}}$	0	
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance	> 9 if $m_{Vh} < 400$ GeV, $> 6.6 + 0.01 \cdot m_{Vh}/(1\ GeV)$ if 400 GeV $< m_{Vh} <$ 700 GeV, > 13.6 if $m_{Vh} > 700$ GeV,	
	2-lepton selection	
Leading lepton p_{T} [GeV]	> 27	> 27
Sub-leading lepton p_{T} [GeV]	> 20	> 25
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ [$\sqrt{\mathrm{GeV}}$]	$< 1.15 + 8 \times 10^{-3} \cdot m_{Vh}/(1\ GeV)$	
$p_{\mathrm{T},\ell\ell}$ [GeV]	$> 20 + 9 \cdot \sqrt{m_{Vh}/(1\ GeV) - 320}$ for m_{Vh} ¿ 320 GeV	
$m_{\ell\ell}$ [GeV]	$[\max[40,\ 87 - 0.030 \cdot m_{Vh}/(1\ GeV)],\ 97 + 0.013 \cdot m_{Vh}/(1\ GeV)]$	

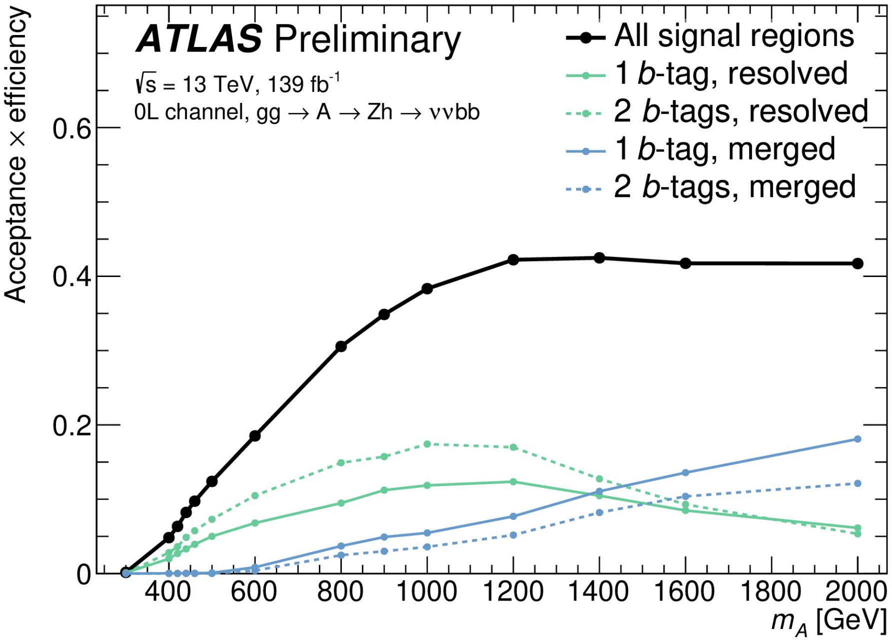


ATLAS-CONF-2020-043

Search for pseudo scalars in A → Zh decays:

Product of acceptance and efficiency for the A → Zh → ννbb, ℓℓbb as a function of the resonance mass for the 0-lepton SR and for the 2-lepton SR

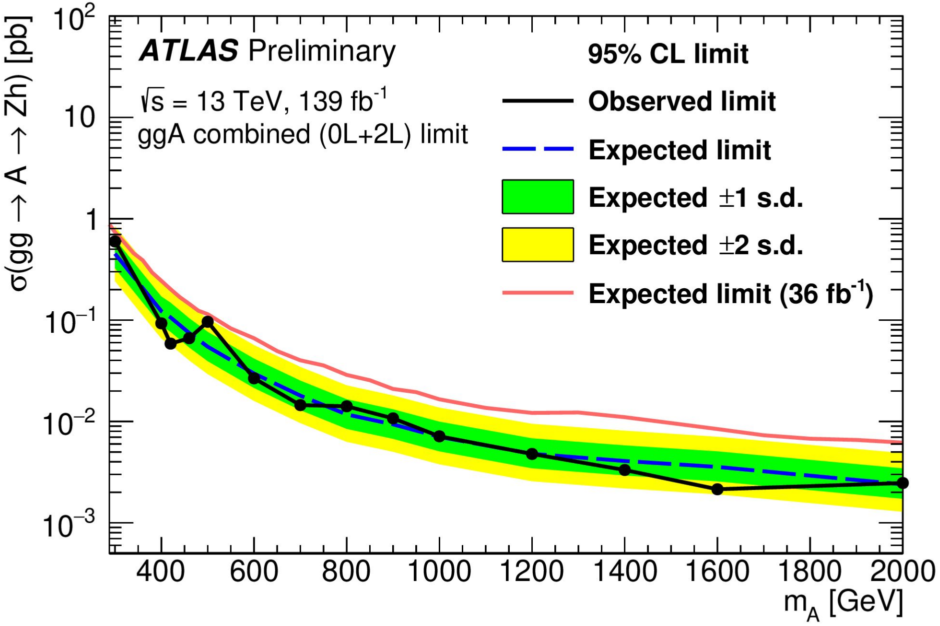




ATLAS-CONF-2020-043

Search for pseudo scalars in A → Zh decays:

Upper limits at the 95% CL on the product of the cross section for gg → A and their respective branching fraction to Zh from the combination of the 0-lepton and 2-lepton channels.



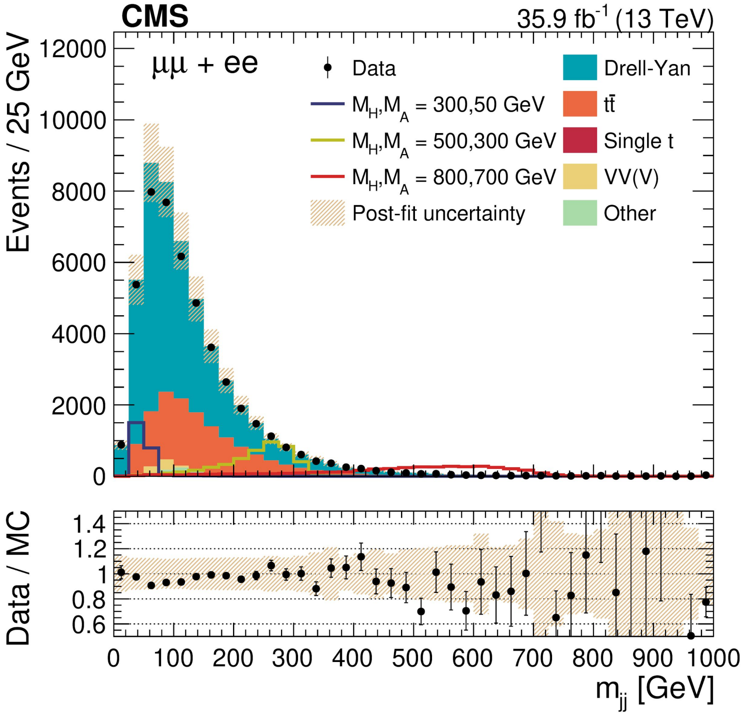
Process	Quantity/source	Value
Signal	acceptance	2-7%
	PS, ISR/FSR, PDF	S
	p_T^{miss} (0-lep.)	S
$t\bar{t}$, single top	0-lep. norm.	float
	2-lep. norm.	float
	0-lep. resolved / merged	9–20%
	2-lep. resolved / merged	18%
	0-lep. m_{jj} SR / m_{jj} CR	2–12%
	2-lep. SR / $e\mu$ CR	1.2%
	PS, ISR/FSR, ME, PDF	S
	p_T^{miss} (0-lep.)	S
Z+hf	norm.	float
	resolved / merged	10%
	0-lep. SR / m_{jj} CR	5–12%
	0-lep. / 2-lep.	15%
	generator, PDF, scale	S
	p_T^{bb} reweight.	S
	p_T^{miss} (0-lep.)	S
Z+hl	norm.	float
	resolved / merged	20%
	0-lep. SR / m_{jj} CR	3–20%
	0-lep. / 2-lep.	12%
	generator, PDF, scale	S
	p_T^{bb} reweight.	S
	p_T^{miss} (0-lep.)	S

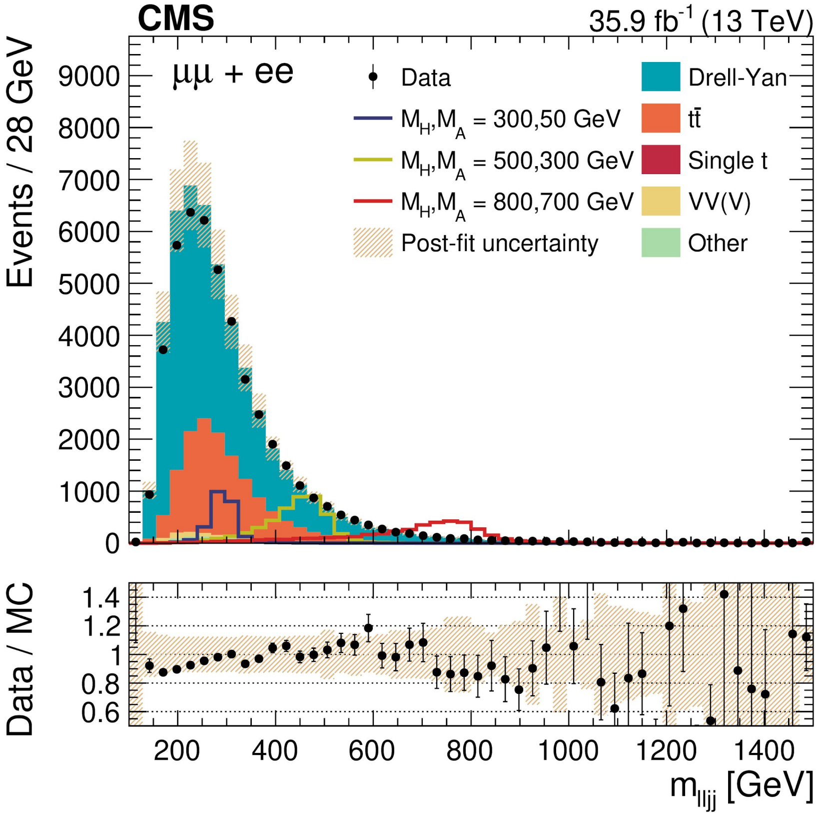
Process	Quantity/source	Value
Zl	norm.	19%
	resolved / merged	8%
	0-lep. SR / m_{jj} CR	5–20%
	0-lep. / 2-lep.	8 %
	generator, PDF, scale	S
	p_T^{bb} reweight.	S
	p_T^{miss} (0-lep.)	S
W+hf	norm.	20%
	resolved / merged	46%
	0-lep. SR / m_{jj} CR	5–28%
	generator, PDF, scale	S
	p_T^{miss} (0-lep.)	S
W+hl	norm.	30%
	resolved / merged	35%
	0-lep. SR / m_{jj} CR	2–20%
	generator, PDF, scale	S
	p_T^{miss} (0-lep.)	S
Wl	norm.	30%
	resolved / merged	24%
	0-lep. SR / m_{jj} CR	4–20%
	generator, PDF, scale	S
	p_T^{miss} (0-lep.)	S
SM Vh	0-lep norm.	32%
	2-lep norm.	32%
	p_T^{miss} (0-lep.)	S
Diboson	0-lep norm.	50%
	2-lep norm.	20%
	p_T^{miss} (0-lep.)	S

ATLAS-CONF-2020-043

Search for new neutral Higgs bosons decaying via H→ZA or A → ZH:

- The mjj and mℓℓjj distributions in data and background events after requiring all the analysis selections, for μμ+ee events. The background shapes and normalisations are obtained from simulation. The various signal hypotheses displayed have been scaled to a cross section of 1 pb





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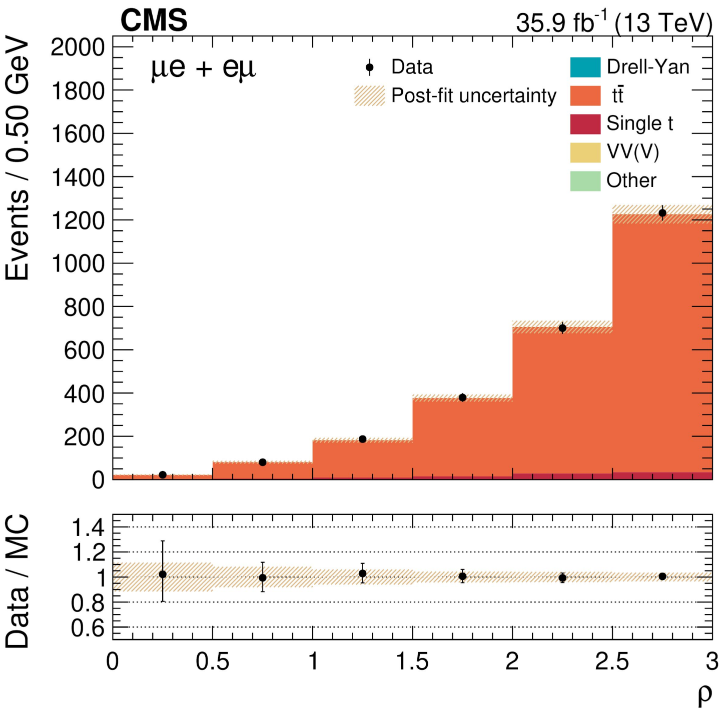
Search for new neutral Higgs bosons decaying via H→ZA or A → ZH:



- **Systematic uncertainties prior to the fit and the variation, in percentages, that they induce on the total event yields for the dominant background and signal processes, under a particular signal hypothesis with mH= 379 GeV and mA= 172 GeV**

Source	Background yield variation	Signal yield variation
Electron identification and isolation	2.7%	2.6%
Integrated luminosity	2.5%	2.5%
Jet energy scale	2.1–2.4%	0.1–0.3%
b tagging (heavy-flavour jets)	2.3%	2.0%
PDFs	1.0%	0.5%
Pileup	0.3–0.9%	0.7–1.3%
b tagging (light-flavour jets)	0.7–0.8%	<0.1%
Muon identification and isolation	0.5%	0.4%
Trigger efficiency	0.1–0.3%	0.1–0.3%
Jet energy resolution	0.2%	0.2%
Affecting only $t\bar{t}$ (31.8% of the total bkg.)		
μ_R and μ_F scales	12.2–12.3%	
$t\bar{t}$ cross section	5.3%	
Affecting only Drell–Yan (64.5% of the total bkg.)		
μ_R and μ_F scales	9.6%	
Drell–Yan cross section	4.9%	
Drell–Yan additional uncertainty	2.1–2.2%	
Simulated sample size	0.5–1.3%	
Affecting only VV (1.1% of the total bkg.)		
μ_R and μ_F scales	4.3–4.8%	
Affecting only signal		
μ_R and μ_F scales		1.8%

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Search for pseudo scalars in A → Zh decays:

- **bbA signal modelling**
  - For bbA channel, ggA event yields are rescaled via:

$$\text{Total signal yield} = \text{gg} \rightarrow \text{A yield} \left(1 + \epsilon_{\text{b}\bar{\text{b}}\text{A}/\text{gg}\rightarrow\text{A}} \frac{\sigma_{\text{b}\bar{\text{b}}\text{A}}}{\sigma_{\text{gg}\rightarrow\text{A}}}\right)$$

with an estimated selection efficiency ratio:

$$\epsilon_{\text{b}\bar{\text{b}}\text{A}/\text{gg}\rightarrow\text{A}} = 0.76$$

Process	$\ell\ell+\text{e}\tau_\text{h}$	$\ell\ell+\mu\tau_\text{h}$	$\ell\ell+\tau_\text{h}\tau_\text{h}$	$\ell\ell+\text{e}\mu$
h (125 GeV)	0.77 ± 0.02	1.39 ± 0.03	1.28 ± 0.04	0.45 ± 0.01
$\text{ZZ}\rightarrow4\ell$	6.48 ± 0.13	11.38 ± 0.25	7.59 ± 0.20	4.57 ± 0.09
Other	0.10 ± 0.01	0.24 ± 0.02	0.04 ± 0.01	0.69 ± 0.04
Reducible	5.52 ± 0.42	9.12 ± 0.93	6.68 ± 0.65	2.04 ± 0.24
Total background	12.88 ± 0.45	22.13 ± 0.94	15.58 ± 0.68	7.74 ± 0.28
$\text{A}\rightarrow\text{Zh}$, $m_\text{A}=300\,\text{GeV}$, $\sigma\mathcal{B}=20\,\text{fb}$	4.13 ± 0.18	7.32 ± 0.30	7.01 ± 0.40	2.26 ± 0.10
Observed	13	22	14	12

Background and signal expectations together with the numbers of observed events, for the signal region distributions after a background-only fit

Channel	Z boson selection	h boson selection
$\ell\ell+\text{e}\tau_\text{h}$	Opposite-charge, same-flavor light leptons $60 < m_{\ell\ell} < 120\,\text{GeV}$	$\epsilon^\text{e}_\text{id.}=80\%$, $I^\text{e}<0.15$, $\epsilon^{\tau_\text{h}}_\text{id.+iso.}=70\%$
$\ell\ell+\mu\tau_\text{h}$		$\epsilon^\mu_\text{id.}>99\%$, $I^\mu<0.15$, $\epsilon^{\tau_\text{h}}_\text{id.+iso.}=70\%$
$\ell\ell+\tau_\text{h}\tau_\text{h}$		$\epsilon^{\tau_\text{h}}_\text{id.+iso.}=70\%$, $L^\text{h}_\text{T}>60\,\text{GeV}$
$\ell\ell+\text{e}\mu$		$\epsilon^\text{e}_\text{id.}=80\%$, $I^\text{e}<0.15$, $\epsilon^\mu_\text{id.}>99\%$, $I^\mu<0.15$

Kinematic selection requirements for each A boson decay channel, applied on top of the looser selections and b jet veto

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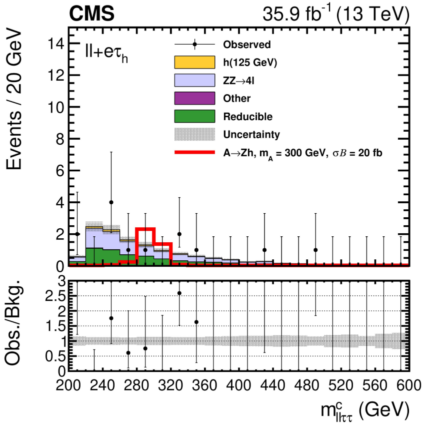
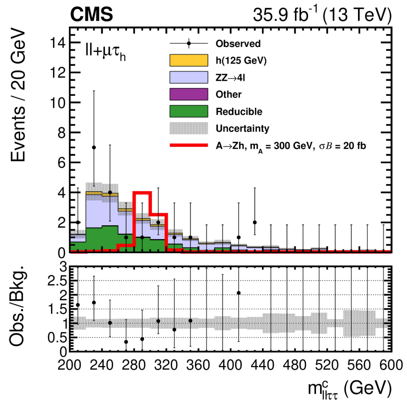
Search for pseudo scalars in A → Zh decays:

Table 3: Sources of systematic uncertainty. The sign † marks the uncertainties that affect both the shape and normalization of the final $m^{c}_{\ell\ell\tau\tau}$ distributions. Uncertainties that only affect the normalizations have no marker. For the shape and normalization uncertainties, the magnitude column lists an approximation of the associated change in the normalization of the affected processes.

Source of uncertainty	Process	Magnitude
τ_h id. & isolation	All simulated processes	5%
τ_h energy scale† (1.2% energy shift)	All simulated processes	<2%
e id. & isolation	All simulated processes	2%
e trigger	All simulated processes	2%
μ id. & isolation	All simulated processes	2%
μ trigger	All simulated processes	2%
b jet veto	All simulated processes	4.5% heavy flavor, 0.15% light flavor or gluon
$qq \to ZZ$ theoretical uncertainty	$qq \to ZZ$	4.8%
PDF set uncertainty	Zh, Wh, $gg \to h \to ZZ$, and $t\bar{t}h$	Varies from 1.6 to 3.6% (see text)
RF scale uncertainty	Zh, Wh, $gg \to h \to ZZ$, and $t\bar{t}h$	Varies from 0.7 to 7.5% (see text)
$gg \to ZZ$ theoretical uncertainty	$gg \to ZZ$	10%
$gg \to ZZ$ NNLO cross section estimation assumptions	$gg \to ZZ$	10%
$t\bar{t}Z$ theoretical uncertainty	$t\bar{t}Z$	25%
$t\bar{t}W$ theoretical uncertainty	$t\bar{t}W$	25%
Triboson theoretical uncertainty	Triboson	25%
Theoretical uncertainty on $\mathcal{B}(h \to \tau\tau)$	Signal, Zh, and Wh	<2%
Reducible background uncertainties:	Reducible background	
e prompt lepton subtraction		<12% in $\ell\ell + e\mu$, <1% in $\ell\ell + e\tau_h$
μ prompt lepton subtraction		<16% in $\ell\ell + e\mu$, <1.5% in $\ell\ell + \mu\tau_h$
τ prompt lepton subtraction		<3.5% in $\ell\ell + e\tau_h$ and $\ell\ell + \mu\tau_h$, <1% in $\ell\ell + \tau_h\tau_h$
Normalization		40% in $\ell\ell + e\tau_h$, $\ell\ell + \mu\tau_h$, $\ell\ell + \tau_h\tau_h$, and $\ell\ell + e\mu$
$\vec{p}_T^{miss}$ energy scale†	All simulated processes	<2%
Limited number of events	All background processes	Statistical uncertainty in individual bins
Integrated luminosity	All simulated processes	2.5%





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