Direct searches for new resonances in multi-boson events

Multi-boson interaction workshop 2021

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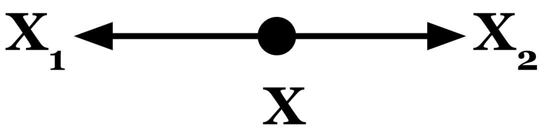
MAX-PLANCK-INSTITUT FÜR PHYSIK

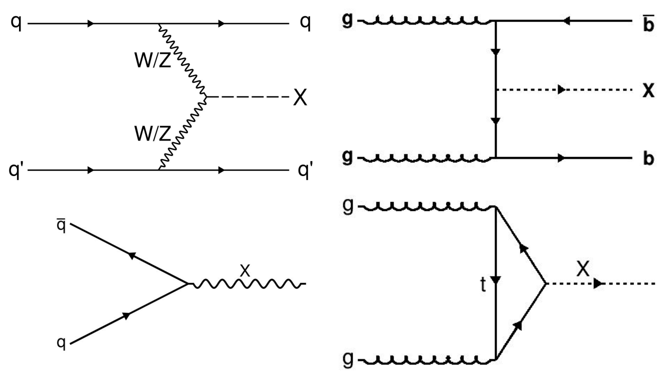
CMS

ATLAS EXPERIMENT

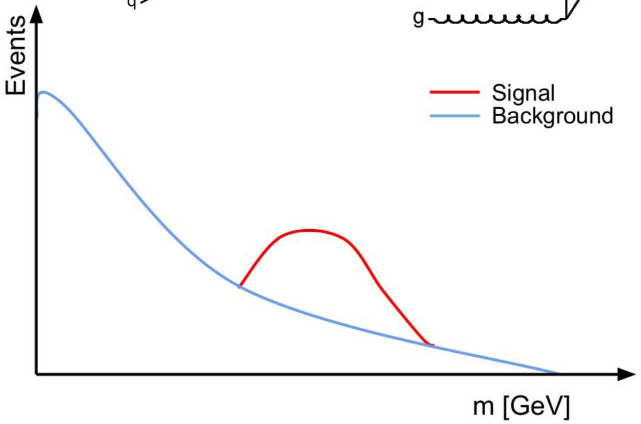
Search for new resonances in multi-boson events:

- **Focus: Searches for a (heavy) resonance X decaying into X_1 and X_2 (with X_1/X_2 = γ, 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
    - multi-jets

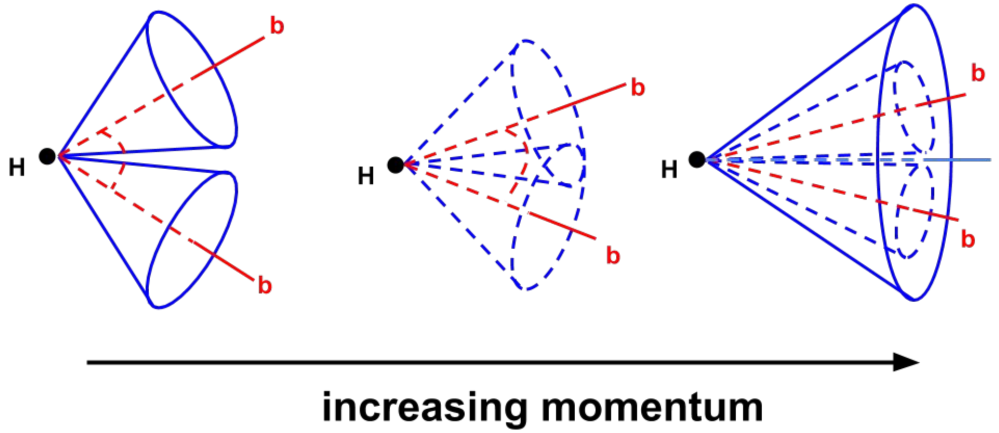


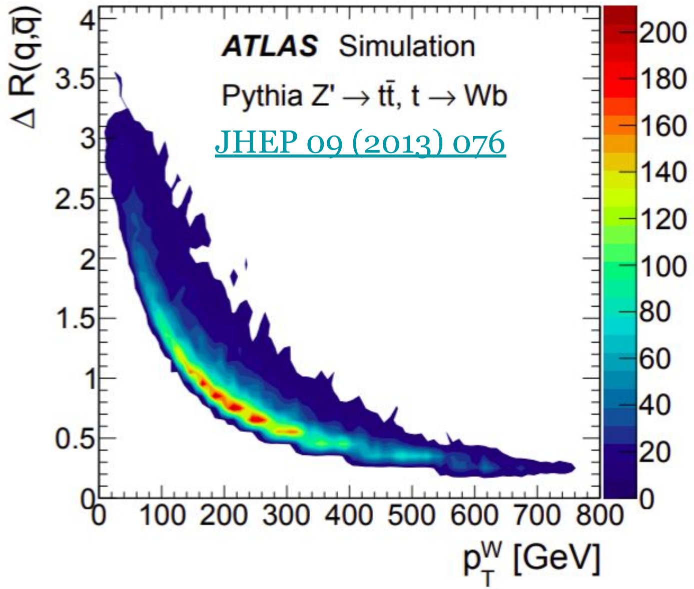


- Most analyses are designed to perform (quasi) **model-independent searches for a bump in a smoothly falling mass spectrum**
  - **Interpretations in generic frameworks:**
    - **Extended Higgs sector:**
      - Two Higgs Doublet Model (2HDM)
    - **Other generic frameworks:**
      - Heavy Vector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



Boosted topologies:



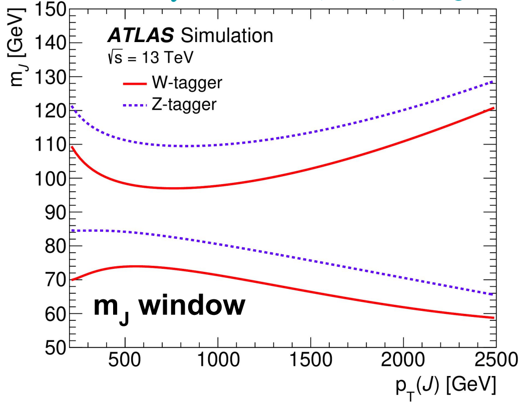


- **Decay products of boosted particles tend to be collimated**
- For p_T^W > 200 GeV and p_T^{Higgs} > 300 GeV decay products tend to have an angular separation smaller than 0.8
  - Partonic structure of decays can no longer be sufficiently described by R=0.4 jets
    - Use R=1.0 jets (ATLAS) or R=0.8 jets (CMS) instead

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

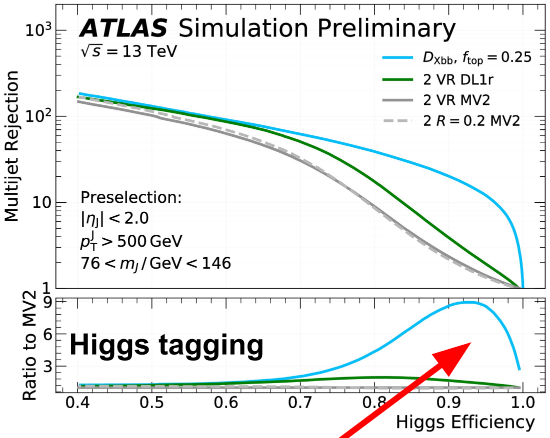
Reconstruction of boosted bosons in ATLAS:

Eur. Phys. J. C 80 (2020) 1165

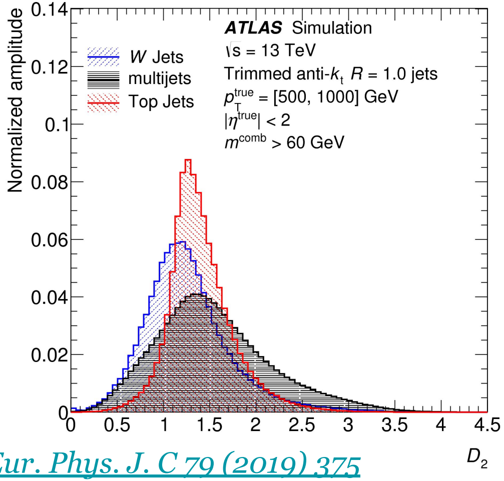


- **Use trimmed R = 1.0 jets:**
  - **W/Z tagging:**
    - m_J window requirement
    - $D_2^{(\beta=1)}$ requirement
    - (N^{trks} requirement)
  - **Higgs tagging:**
    - VR track jets
    - m_J window requirement
    - **DNN (p_T, η, DL1r scores)**

ATL-PHYS-PUB-2020-019



New D_{Xbb} tagger significantly improves our ability to identify Higgs jets



Eur. Phys. J. C 79 (2019) 375

$$D_2^{(\beta)} = \frac{e_3^{(\beta)}}{(e_2^{(\beta)})^3}$$

$$e_2^{(\beta)} = \frac{1}{p_{TJ}^2} \sum_{1 \le i < j \le n_J} p_{Ti} p_{Tj} R_{ij}^{\beta} \ ,$$

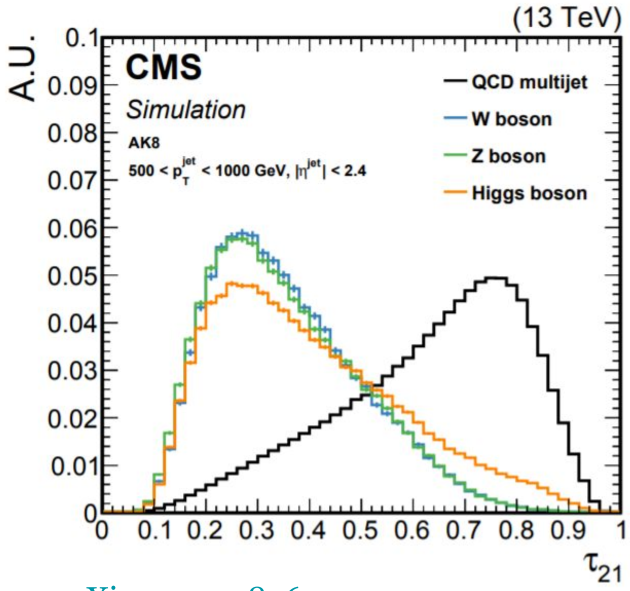
$$e_3^{(\beta)} = \frac{1}{p_{TJ}^3} \sum_{1 \le i < j < k \le n_J} p_{Ti} p_{Tj} p_{Tk} R_{ij}^{\beta} R_{ik}^{\beta} R_{jk}^{\beta}$$

Reconstruction of boosted bosons in CMS:

- **Use groomed (via SoftDrop) R = 0.8 jets:**
  - **W/Z/H tagging:**
    - **Cut based:** Requirements on m_J window and ratio of N-subjettiness τ_{21}
    - **DeepAK8:** Multiclass classifier for the identification of hadronically decaying particles with five main categories (W/Z/H/t/others) using four-vectors and other properties of pflow objects

- **N-subjettiness:**

$$\tau_N = \frac{1}{d_0} \sum_i p_{T,i} \min\left[\Delta R_{1,i}, \Delta R_{2,i}, \ldots, \Delta R_{N,i}\right]$$



arXiv:2004.08262

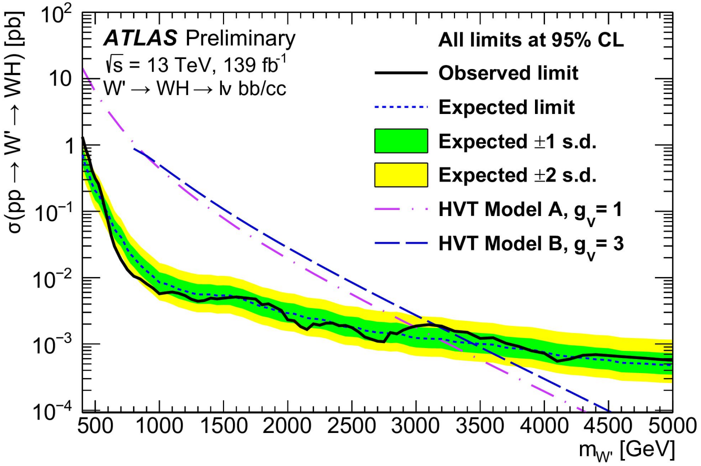
Searches for diboson resonances:

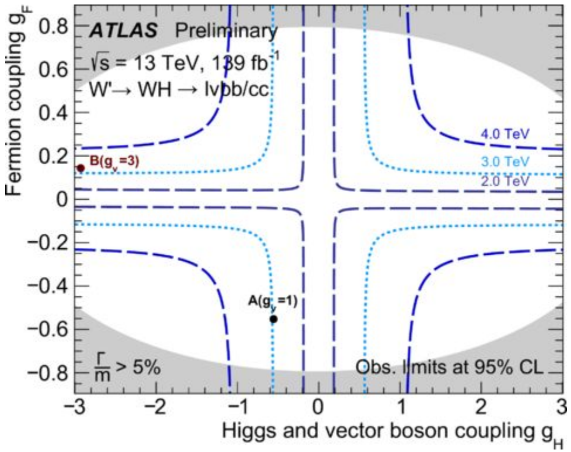
- **Recent results from ATLAS and CMS (covered in this presentation):**
  - Search for resonances in $X \to Wh$ decays [ATLAS): ATLAS-CONF-2021-026
  - Search for resonances in $X \to WW$, WZ and Wh decays (CMS): CMS-PAS-B2G-19-002
  - Search for new particles in $X \to ZZ$, ZH, ZW events (CMS): CMS-PAS-B2G-20-013
  - Search for resonances in $X \to W\gamma$ decays (CMS): arXiv::2106.10509
  - Search for resonances in $X \to W\gamma$ and $X \to Z\gamma$ decays (ATLAS): ATLAS-CONF-2021-041
  - Search for fermiophobic charged Higgs bosons (CMS): arXiv:2104.04762
  - Search for resonances in $X \to aa \to bbbb$ decays (CMS): CMS-PAS-B2G-20-003
  - Search for resonances in $X \to hh \to bbbb$ decays (ATLAS): ATLAS-CONF-2021-035
  - Search for resonances in $X \to hh \to bb\tau\tau$ decays (ATLAS): ATLAS-CONF-2021-030

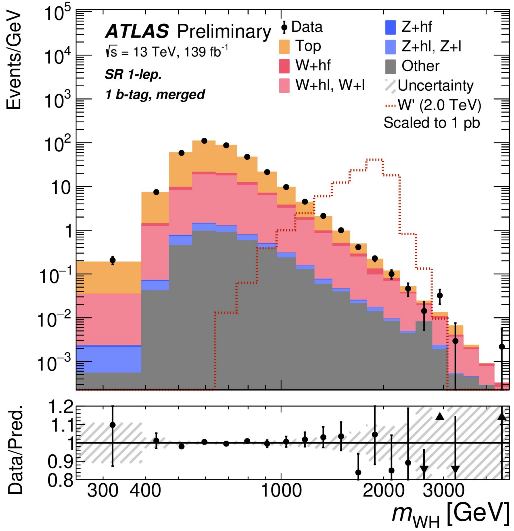
- **Further analysis:**
  - Search for resonances in $H \to hh_s \to bb\tau\tau$ decays (CMS): arXiv:2106.10361
  - Search for a heavy resonance decaying to $\gamma\gamma$ (ATLAS): arXiv:2102.13405
  - Search for resonances in $X \to Zh$ decays (ATLAS): ATLAS-CONF-2020-043
  - Search for resonances in $X \to Zh$ decays (CMS): Eur. Phys. J. C 81 (2021) 688
  - Search for resonances in $X \to hh \to bbbb$ decays (CMS): ATLAS-CONF-2021-035
  - Search for resonances in final states with leptons and bottom quarks (CMS): CMS-PAS-B2G-20-007
  - Search for resonances in $X \to ZW$ and $X \to ZZ$ decays (CMS): CMS-PAS-B2G-20-008

Search for resonances in X → Wh decays:

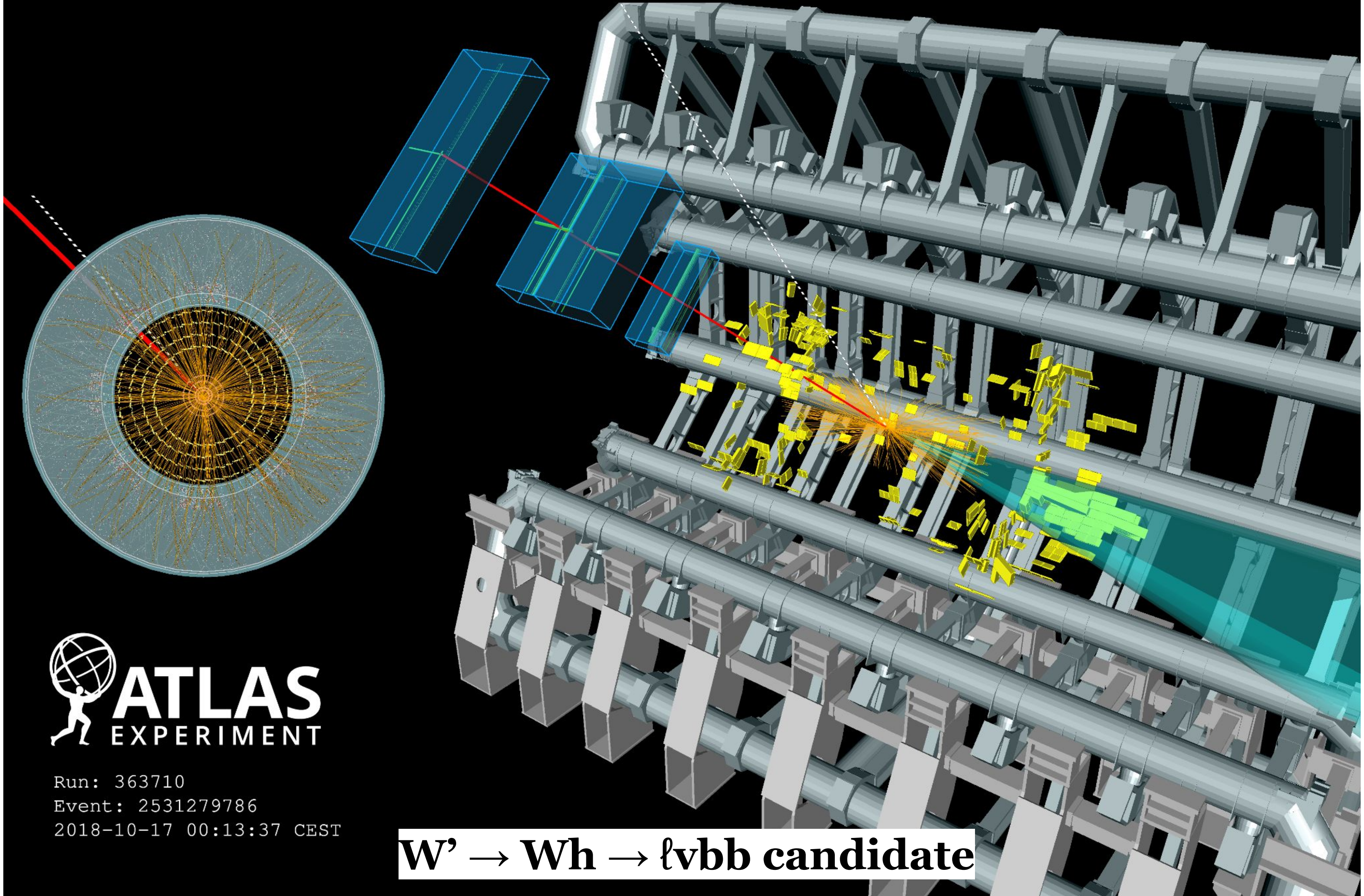
- **Probe resolved and merged ℓνbb (ℓ = μ, e) final states**
- **Analysis strategy:**
  - Search for bumps in $m_{\ell\nu bb}$ spectra
  - Simultaneous fit of all 4 event categories: (resolved, merged) × (1-tag, 2-tag)
- **Dominant systematic uncertainties:**
  - Modelling of backgrounds (top bkg. ME +PS)
  - Large-R jets (mass resolution)







ATLAS-CONF-2021-026

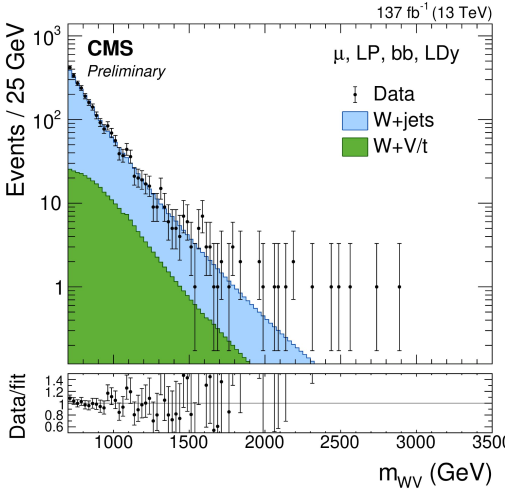


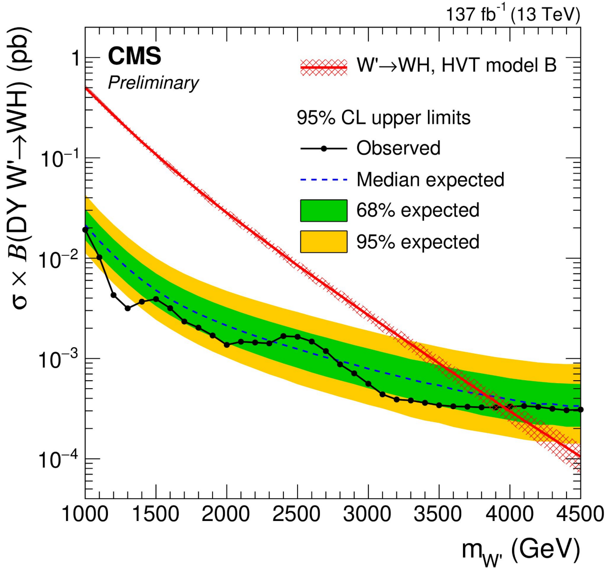
W’ → Wh → ℓvbb candidate

Search for resonances in X → WW, WZ and Wh decays:

- **Probe merged ℓvqq (ℓ = μ, e) final states**
- **Analysis strategy:**
  - Search for bumps in $m_{\ell vqq}$ spectra
  - Simultaneous 2-dimensional fit of the (m_{qq} , $m_{\ell vqq}$) distribution in 24 categories
    - (μ, e) × (HP, LP) × (VBF, bb-tagged, others) × (LDy, HDy)
      - High and low purity (HP & LP) regions based on **τ_N cut**
      - Use low and high rapidity regions (LDy and Hdy)
  - 2d probability density functions are build for signal and bkg.

- **Dominant syst. unc. :**
  - V-tagging
  - Double-b tagging
  - Bkg modelling

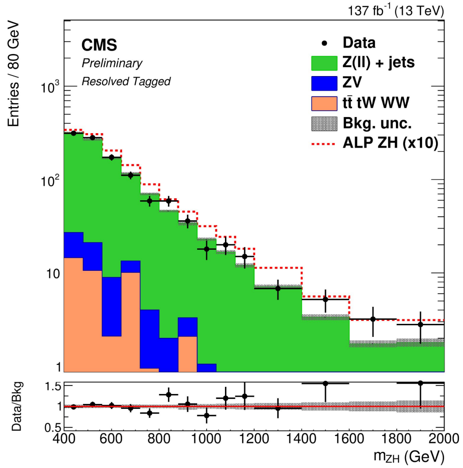


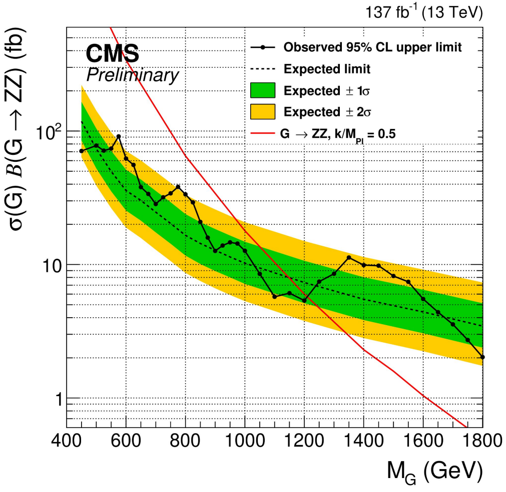


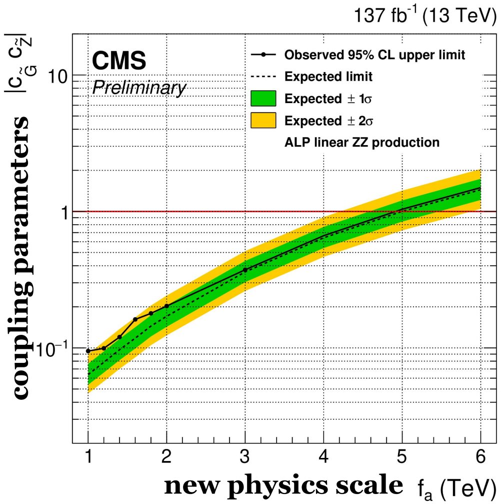
CMS-PAS-B2G-19-002

Search for new particles in X → ZZ, ZH, ZW events:

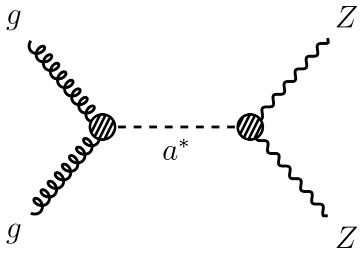
- **Probe resolved and merged ℓℓqq (ℓ = μ, e) final states**
- **Analysis strategy:**
  - Search for bumps in $m_{\ell\ell jj}$ spectra (or excesses in the tails)
    - To probe for new physics in resonant and non-resonant ZZ, ZH, ZW production
  - Simultaneous fit of all 8 event categories:
    - (μμ, ee) × (resolved, merged) × (tagged, untagged)







- **Dominant uncertainties:**
  - Large-R jet mass resolution
  - Z/W-tagging
  - b-tagging



nonresonant ALP-mediated scattering

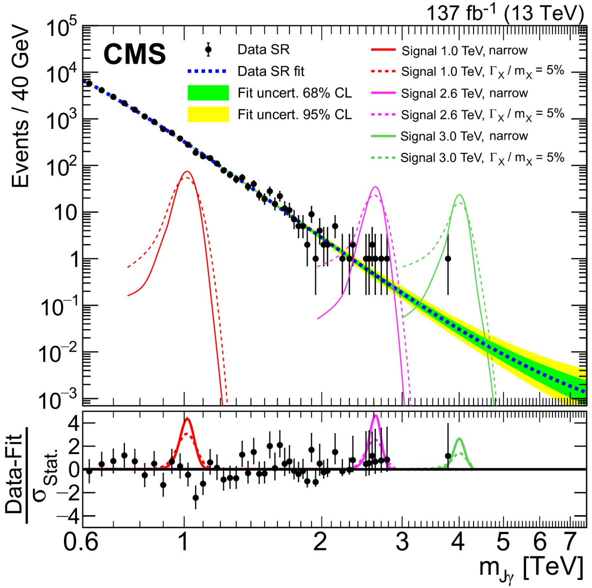
[CMS-PAS-B2G-20-013]

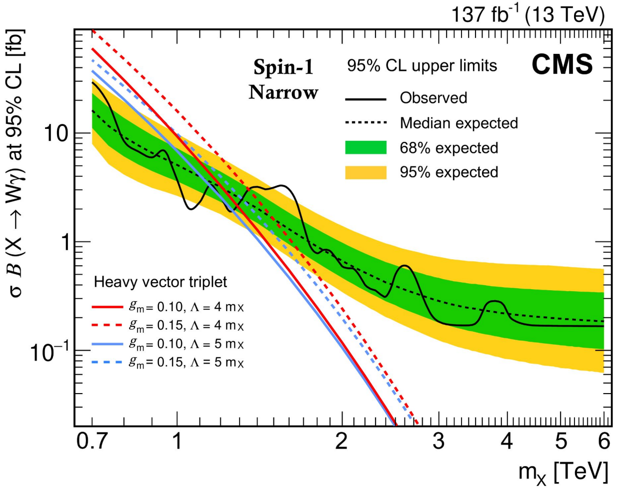
Search for resonances in X → Wγ decays:

- **Search for resonances in (merged) qqγ final states**
  - Probe for particles with spin 0 or 1 hypothesis
- **Analysis strategy:**
  - Use parametric fit function to describe background:

$$\frac{dN}{dm} = p_0(m/\sqrt{s})^{p_1+p_2\log(m/\sqrt{s})+p_3\log^2(m/\sqrt{s})}$$

  - The signal is modeled with the sum of a Crystal Ball function and Gaussian functions





- **Dominant systematic uncertainties:**
  - W-tagging
  - Photon reconstruction and identification

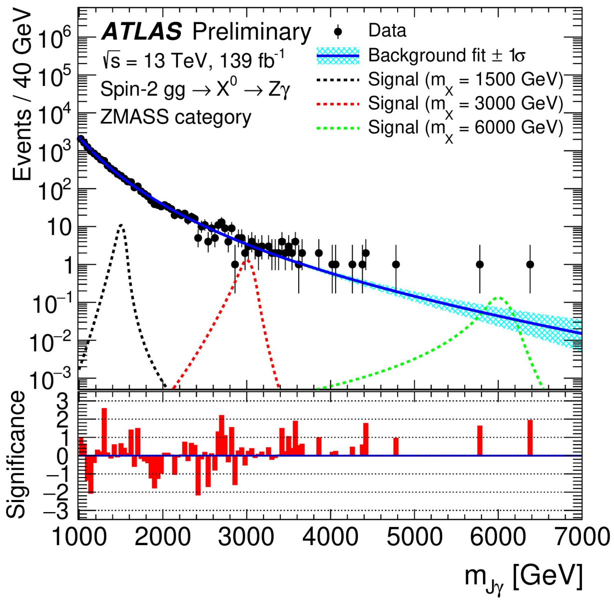
arXiv::2106.10509

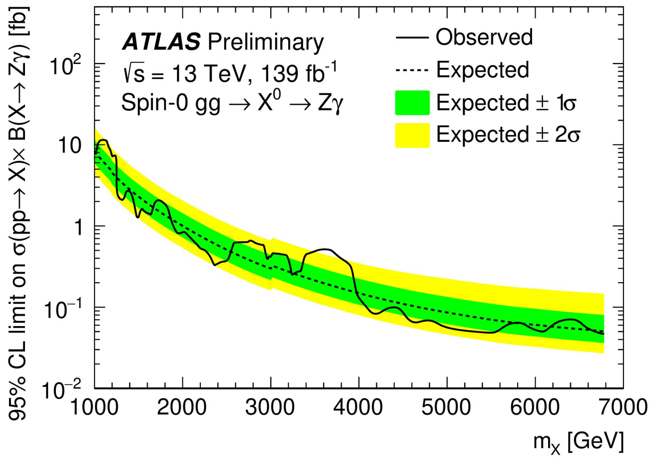
Search for high-mass *Wγ* and *Zγ* resonances:

- **Search for resonances in (merged) qqγ final states**
  - Probe for particles with spin 0, 1 or 2 hypothesis
- **Analysis strategy:**
  - Split events in several non-overlapping signal regions
  - Use parametric fit function to describe background:

$$\mathcal{B}(m_{J\gamma};\boldsymbol{p}) = (1-x)^{p_1} x^{p_2+p_3\log(x)}$$ with: $$x = m_{J\gamma}/\sqrt{s}$$

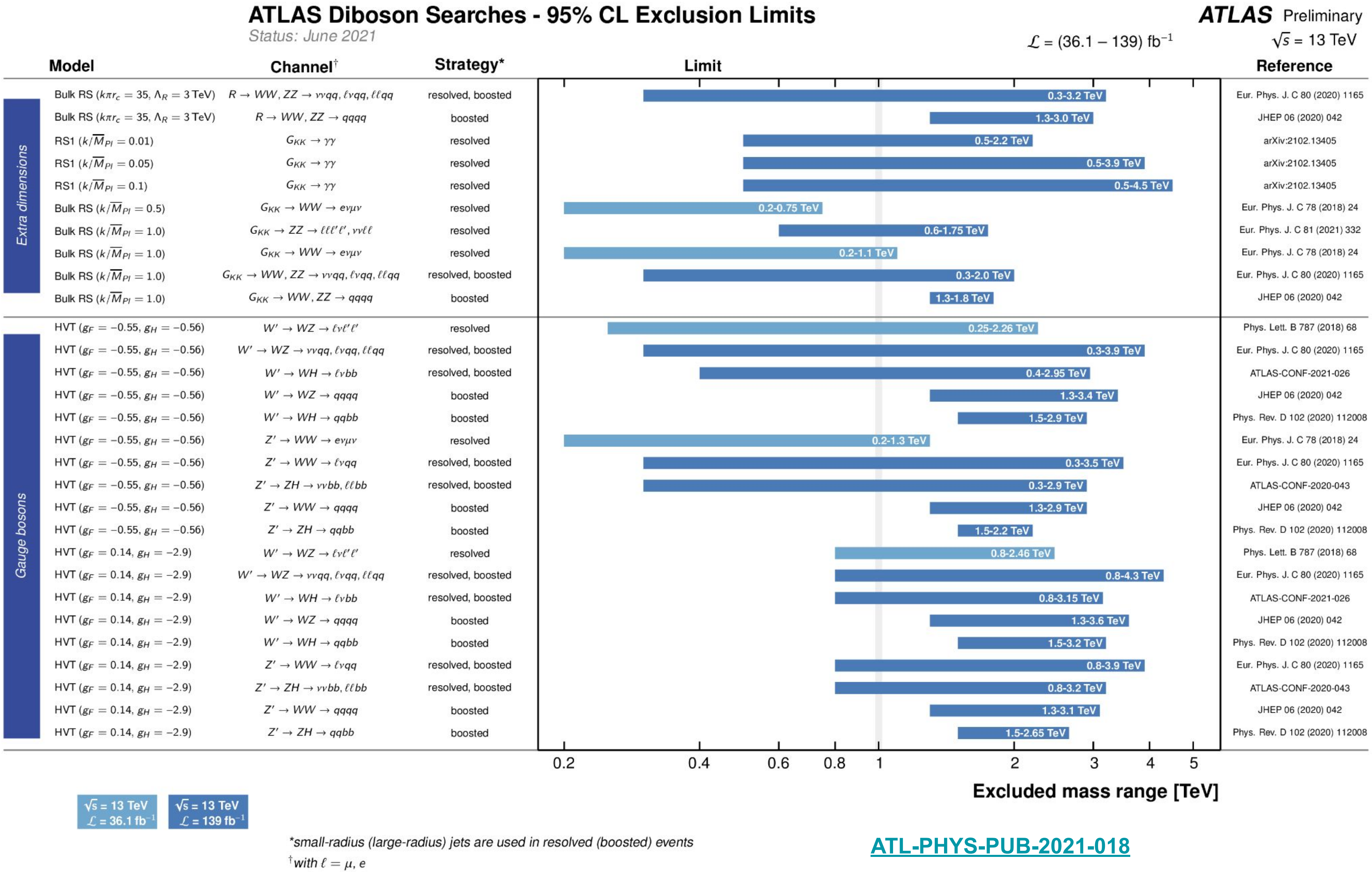
  - The signal is modeled with a double-sided crystal ball function





- **Dominant systematic uncertainties:**
  - Jet mass/energy scale
  - Jet energy resolution

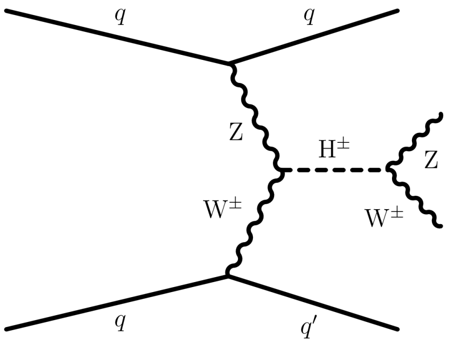
ATLAS-CONF-2021-041

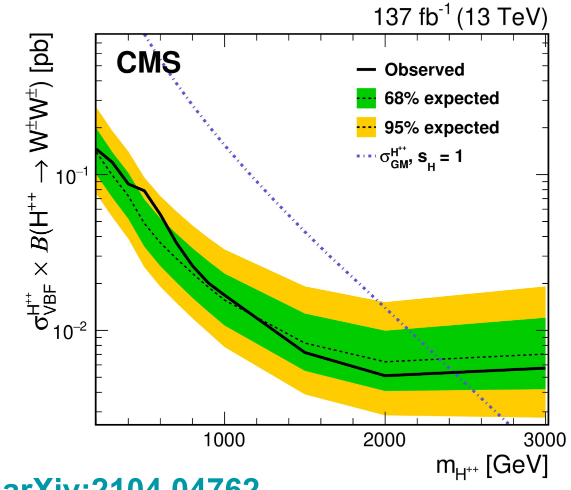


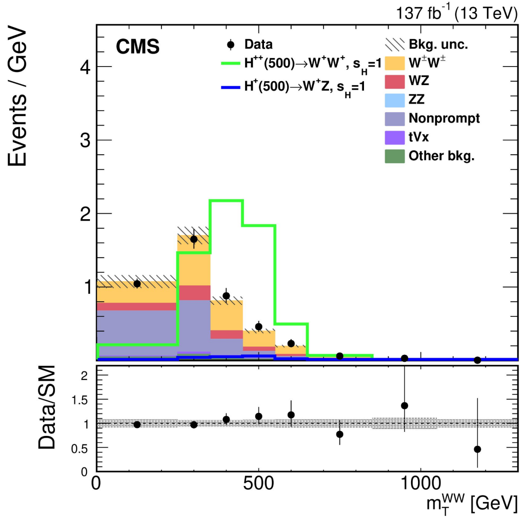
ATL-PHYS-PUB-2021-018

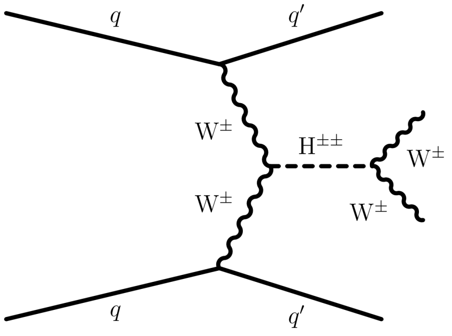
Search for fermiophobic charged Higgs bosons:

- **Search for same-sign ℓνℓνjj and ℓνℓℓjj (ℓ = μ, e) final states**
- **Analysis strategy:**
  - Estimate non-prompt lepton bkg. from data (crucial for ℓνℓν channel)
  - Probe m_T and $m_{\ell\nu\ell\ell}$ distributions for bumps
- **Dominant systematic uncertainties:**
  - Lepton reconstruction/identification
  - Background modelling ($W^{\pm}W^{\pm}$ and WZ)







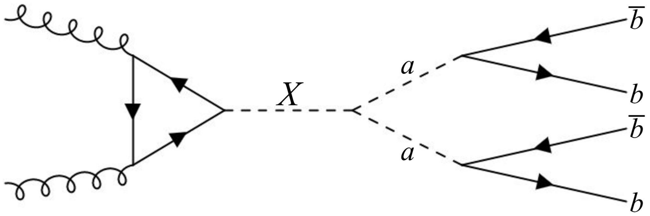


Predicted in e.g. Higgs triplet models

arXiv:2104.04762

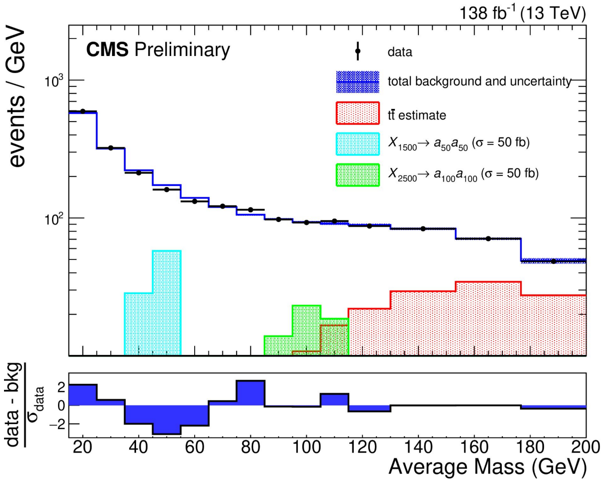
Search for resonances in X → aa→ bbbb decays:

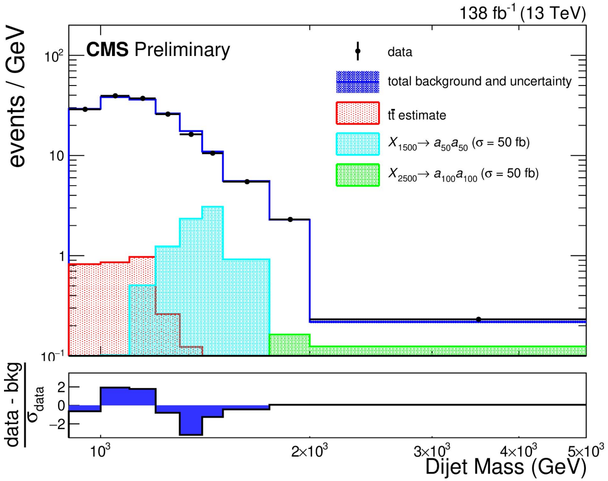
- **Probe merged bbbb final states**
- **Analysis strategy:**
  - Reconstruct a→ bb decays using large-R jets and **double b-tagging** (via the so-called D^{bb} score)
  - Search for localized excess in the two-dimensional distributions of the **average jet mass** and **dijet mass**
  - QCD background estimate obtained via extrapolations from CR to SR



CMS-PAS-B2G-20-003

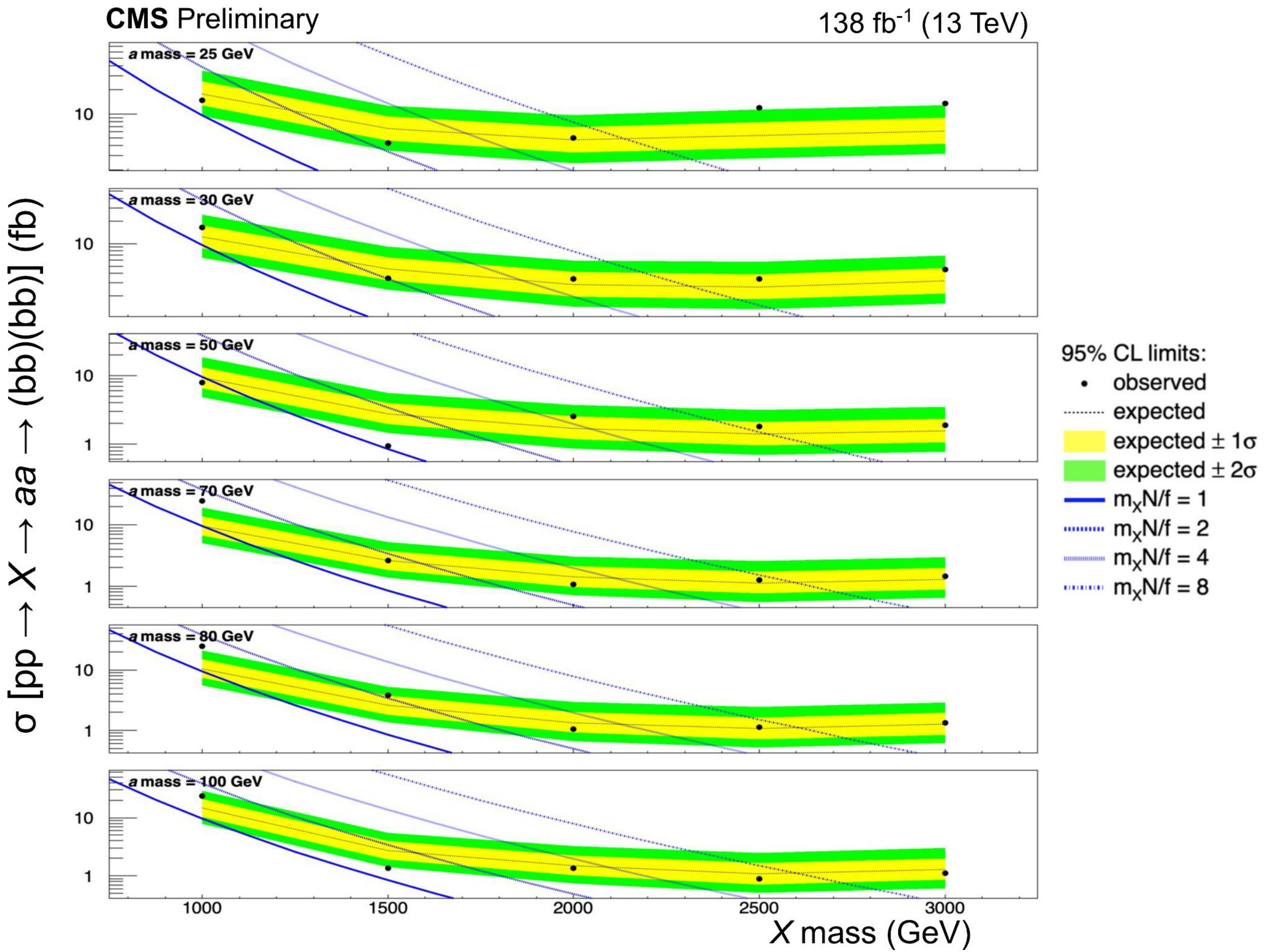
- **Use several SRs and CRs**
  - Definition based on::
    - Jet masses asymmetry
    - Pseudorapidity gap
    - D^{bb} score





- **Dominant systematic uncertainties:**
  - Background modelling
  - Double b-tagging

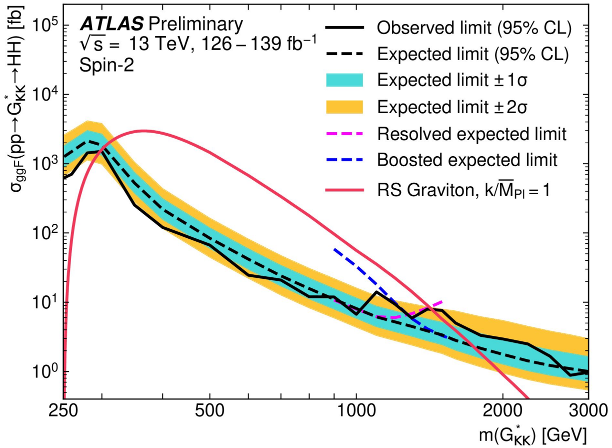
Search for resonances in X → aa→ bbbb decays:

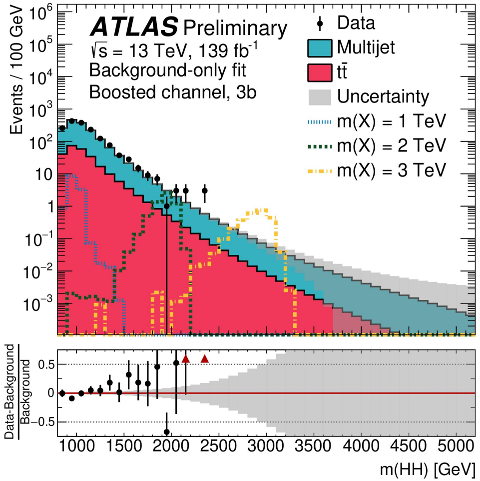


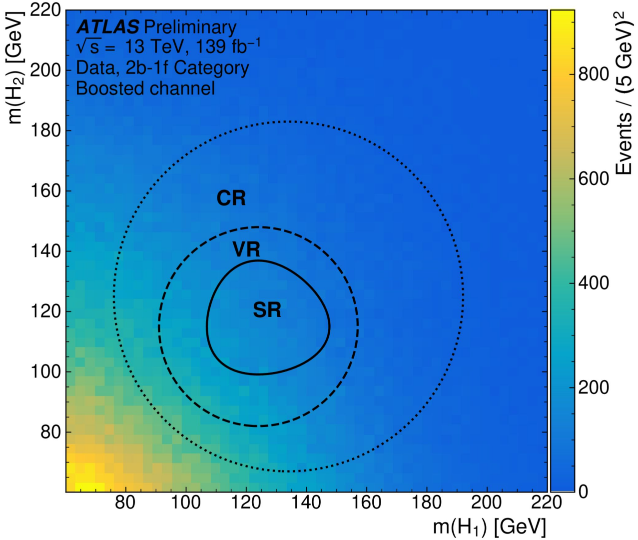
CMS-PAS-B2G-20-003

Search for resonances in X → hh→ bbbb decays:

- **Search for resolved and merged bbbb final states**
- **Analysis strategy:**
  - Resolved/Boosted events are classified into the SR/VR/CR based on their m_{H1} and m_{H2} values
  - Probe for bumps in m_{bbbb} spectra
  - Train neural network for background estimation
    - **Extrapolate background distribution from CRs to SR**
- **Dominant systematic uncertainties:**
  - Background m_{HH} shape
  - Jet momentum/mass resolution







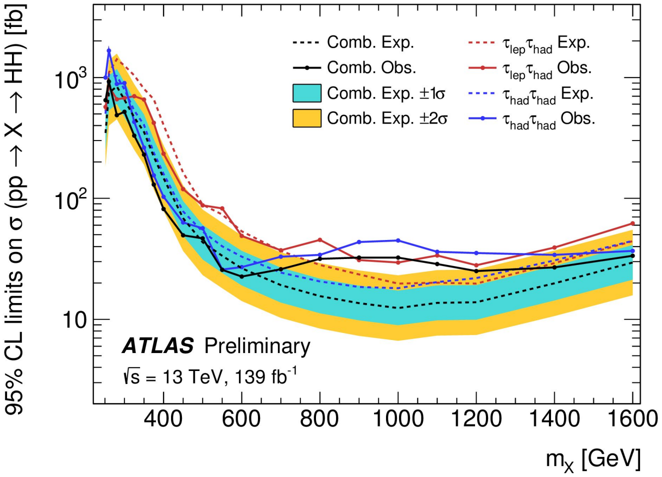
ATLAS-CONF-2021-035

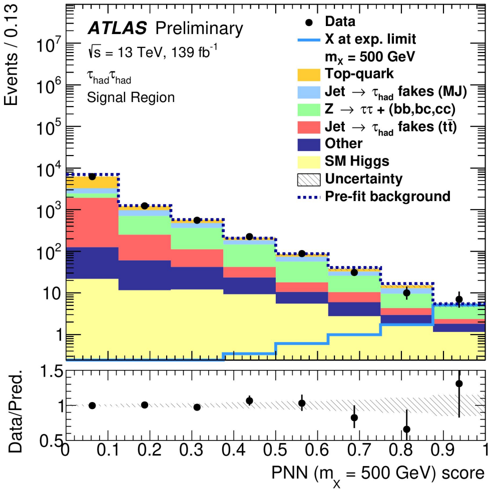
Search for resonances in $X \rightarrow hh \rightarrow bb\tau\tau$ decays:

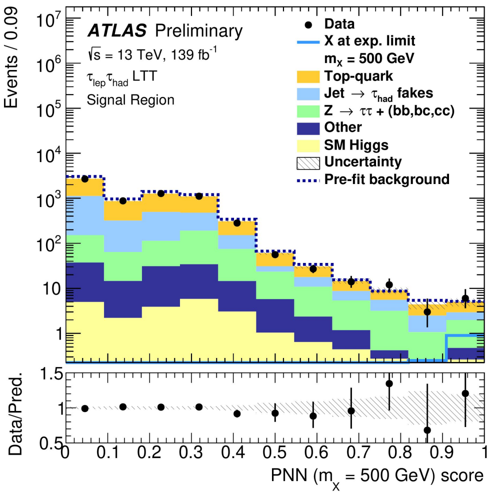
ATLAS-CONF-2021-030

- **Search for resolved $bbe\tau_h$, $bb\mu\tau_h$, and $bb\tau_h\tau_h$ final states**
- **Analysis strategy:**
  - Train MVAs for the different event categories
  - Simultaneous fit to the three MVA output distributions and to the $m_{\ell\ell}$ distribution in the Z + HF CR
- **Dominant systematic uncertainties:**
  - MC statistics
  - Jet energy scale/resolution

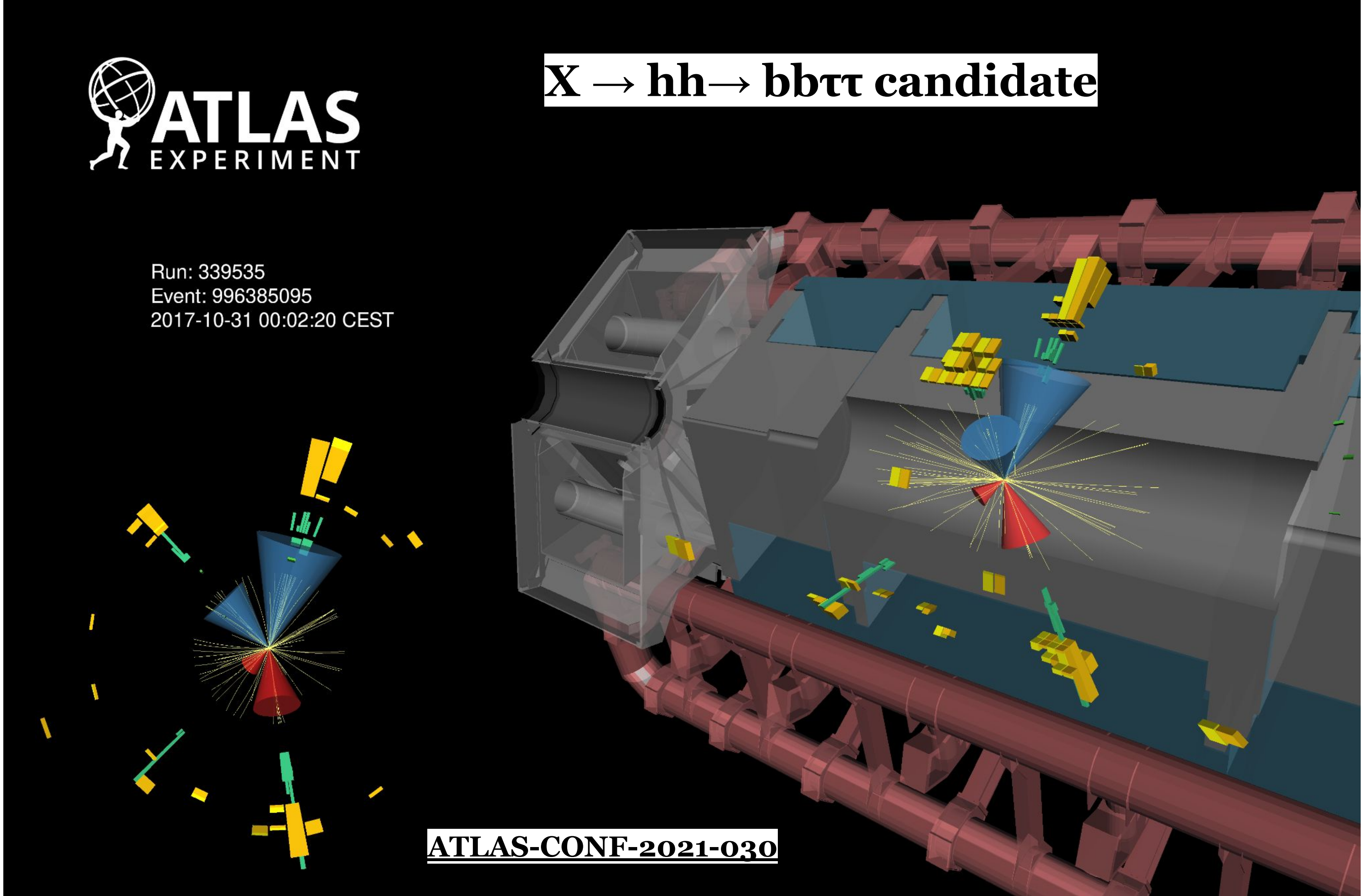
Largest local (global) deviation wrt SM expectations was found to be 3.0σ (2.0σ) for m_{HH} = 1TeV





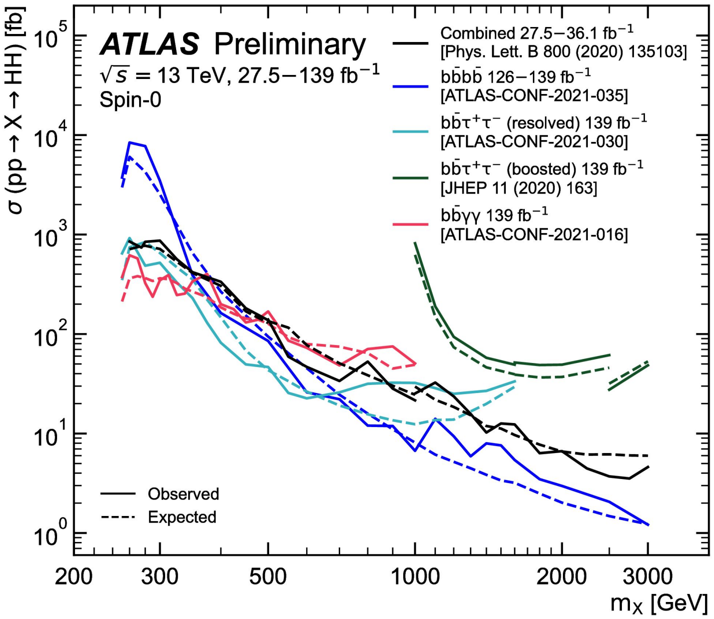


X → hh→ bbττ candidate

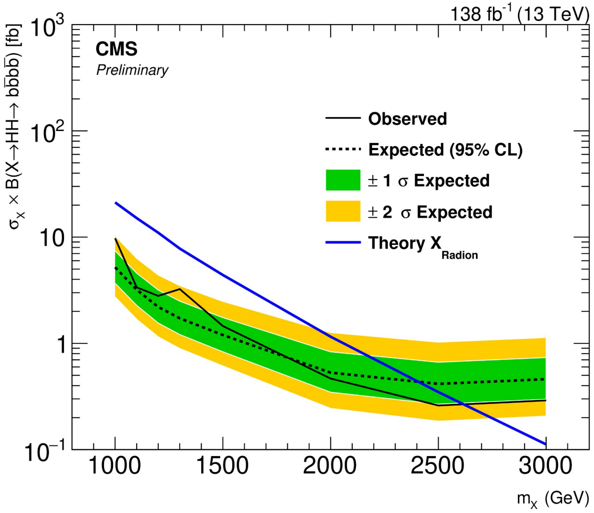


ATLAS-CONF-2021-030

Summary of recent X → hh resonance searches



ATL-PHYS-PUB-2021-031



CMS-PAS-B2G-20-004

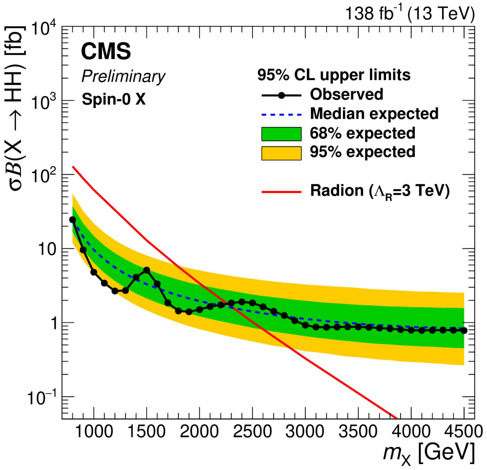
Search for resonances decaying via:

- X → HH → bbbb

Search for resonances decaying via:

- X → HH → bbWW* → bbℓνqq
- X → HH → bbWW*→ bbℓνℓν
- X → HH → bbττ → bbℓννℓνν

CMS-PAS-B2G-20-007



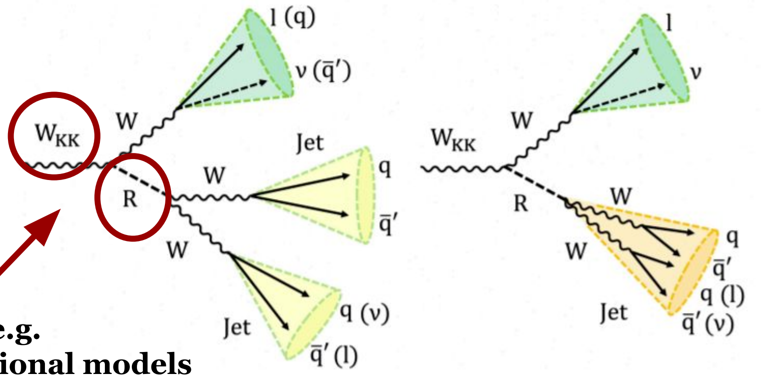
Searches for multi-boson resonances:

- **Recent results from ATLAS**
  - Search for doubly and singly charged Higgs bosons decaying into vector bosons in multi-lepton final states with the ATLAS detector using proton-proton collisions at $\sqrt{s}$ = 13 TeV (JHEP 06 (2021) 146)
  - Search for a heavy Higgs boson decaying into a Z boson and another heavy Higgs boson in the $\ell\ell bb$ and $\ell\ell WW$ final states in pp collisions at $s\sqrt{}$=13 TeV with the ATLAS detector (Eur. Phys. J. C. 81 (2021) 396)

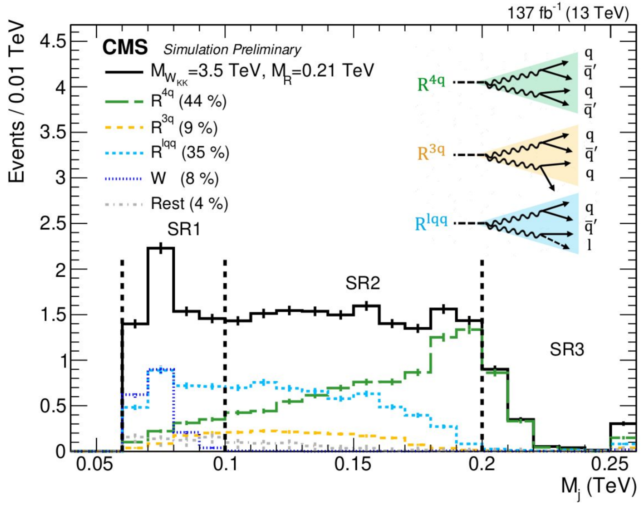
- **Recent results from CMS**
  - Search for resonances decaying to triple W-boson final states in proton-proton collisions at $\sqrt{s}$ = 13 TeV (B2G-20-001)
  - Search for resonances decaying to three W bosons in the hadronic final state at $\sqrt{s}$ = 13 TeV (B2G-21-002)

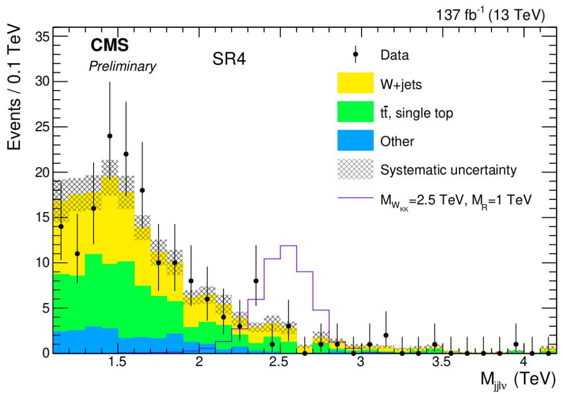
Search for resonances decaying to triple W-boson final states:

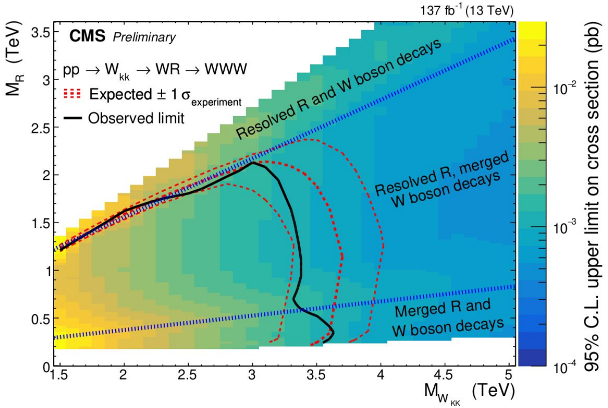
- **Search for cascade decays leading to merged ℓνqqqq (ℓ = μ, e) final states**
  - Study events with one or two Large-R jets
- **Analysis strategy:**
  - Probe for bumps in $m_{j\ell\nu}$ and $m_{jj\ell\nu}$ spectra
- **Dominant systematic uncertainties:**
  - Multi-prong jet tagging
  - Background modelling



Predicted in e.g. extra-dimensional models



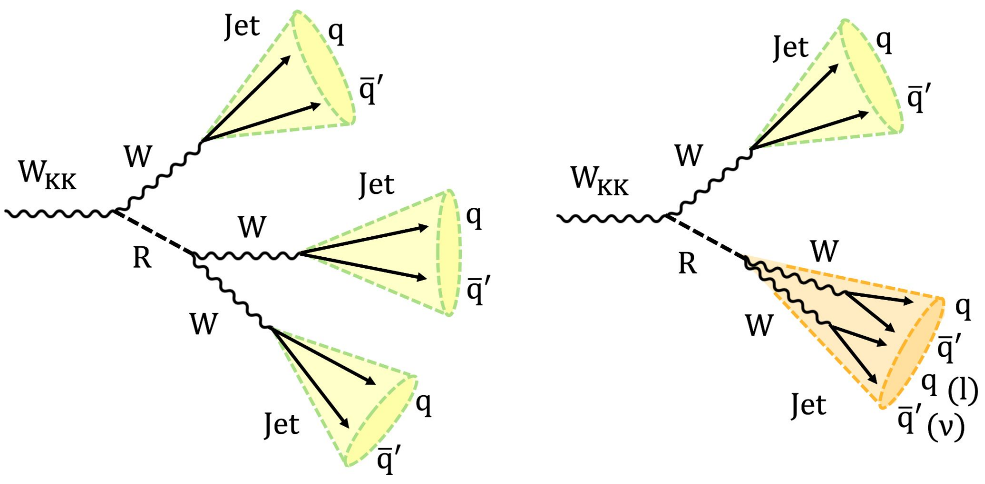


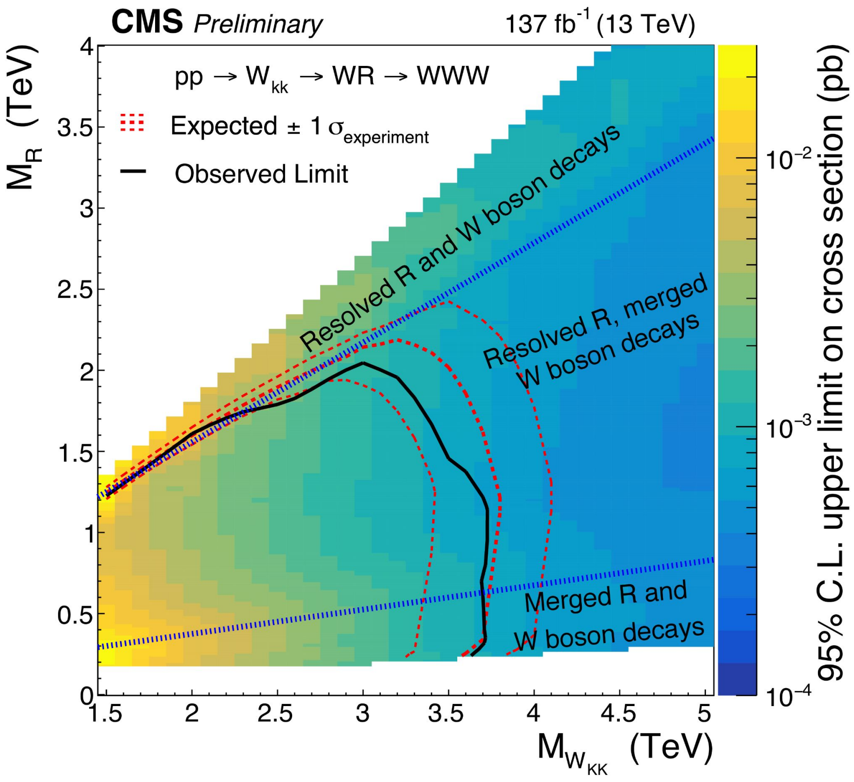


CMS-PAS-B2G-20-001

Search for resonances decaying to triple W-boson final states:

- **Search for cascade decays leading to merged qqqqqq final states**
  - Study events with two or three Large-R jets



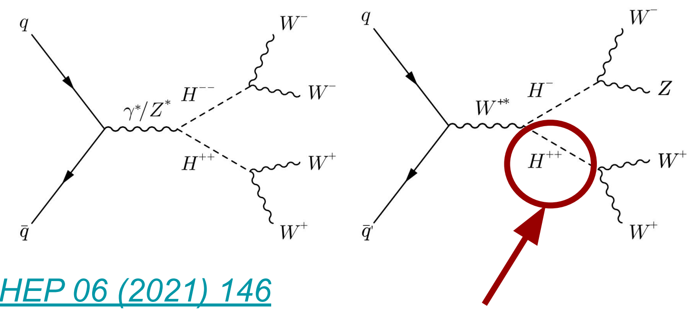


Expected and observed upper limits at 95% CL on the product cross section of the signal from combining the all-hadronic and single-lepton searches.

CMS-PAS-B2G-21-002

Search for doubly and singly charged Higgs bosons:

- **Probe multi-lepton final states ($2\ell^{SC}$, 3ℓ, 4ℓ)**
- **Analysis strategy:**
  - Define signal regions (angular distances, invariant masses)
  - Probe for excess of observed signal region yields
  - Simultaneous fit of the three signal regions
- **Dominant systematic uncertainties:**
  - Non-prompt lepton estimation
  - MC statistics



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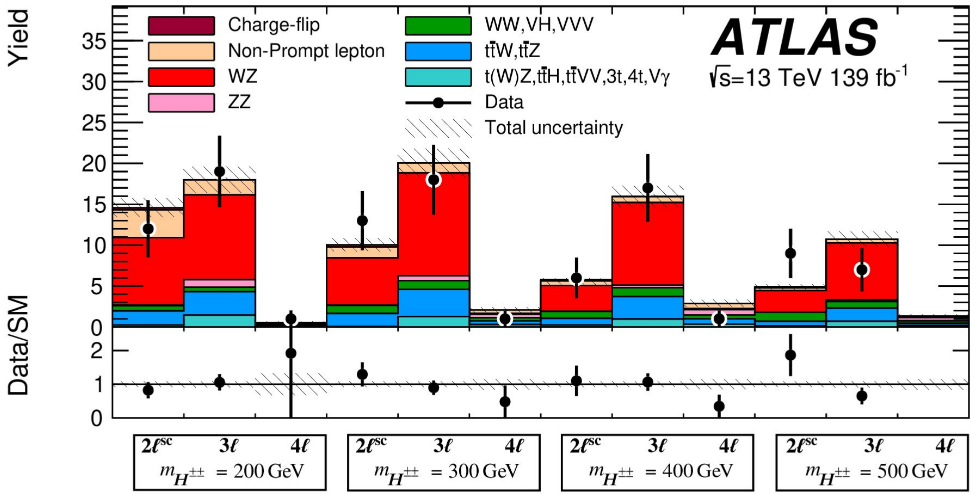
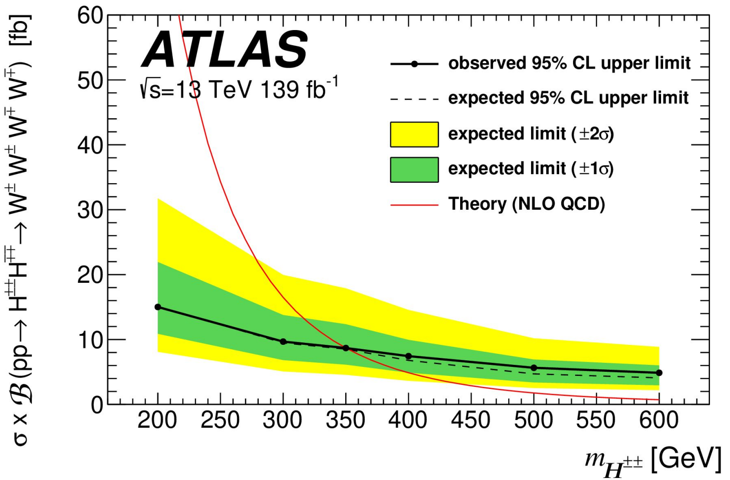
Predicted in Higgs triplet models (needed for e.g. type-II seesaw mechanism)





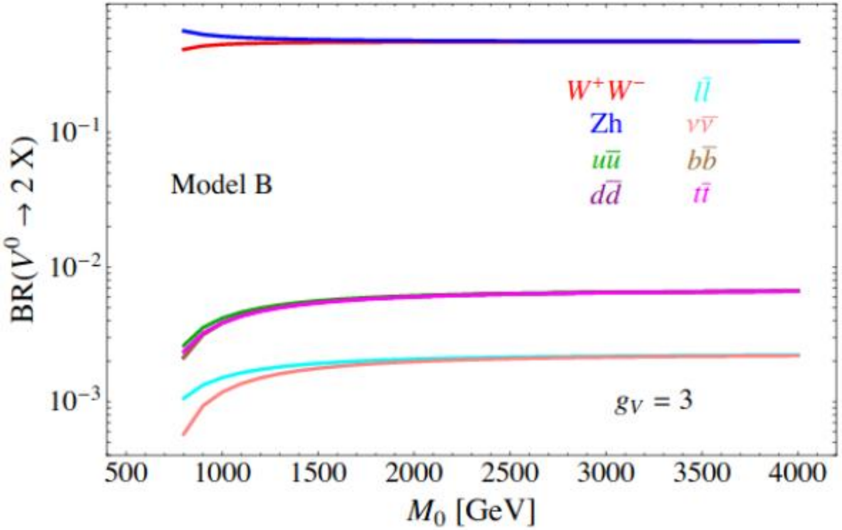
Concluding remarks:

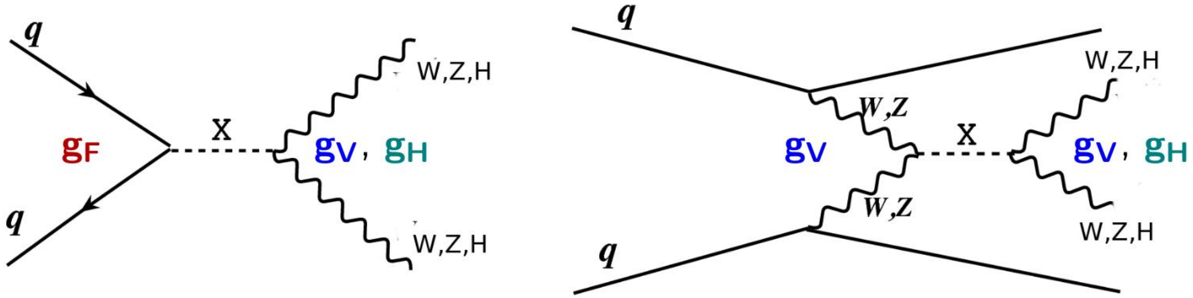
- **Many interesting searches for new (heavy) resonances are ongoing within ATLAS and CMS**
  - Presented only a few highlights of available results.
    - Additional results can be found via the **ATLAS** and **CMS** publication pages
  - No significant hint for physics beyond the SM has been observed so far
  - Many results based on the full Run-2 data set are expected in the next month/years
- **Should think about uncovered final states:**
  - ATLAS and CMS only recently started to search for cascade decays

Back-up

Heavy vector triplet (HVT) models

- **Heavy vector triplet** (HVT) as an example for a simplified model:
  - Simply introduces an additional SU(2) field to the SM
    - Results in a Z' and W'
    - Coupling to SM particles governed by model parameters g_V , g_F , g_H
  - Representative for:
    - Minimal Walking Technicolour
    - Little Higgs models
    - Composite Higgs models
    - Models with extra dimension

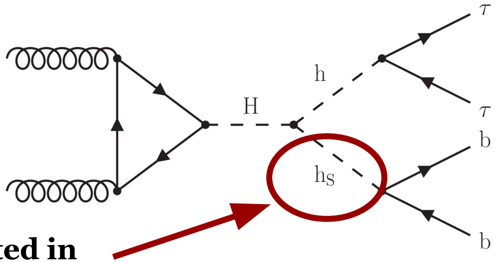




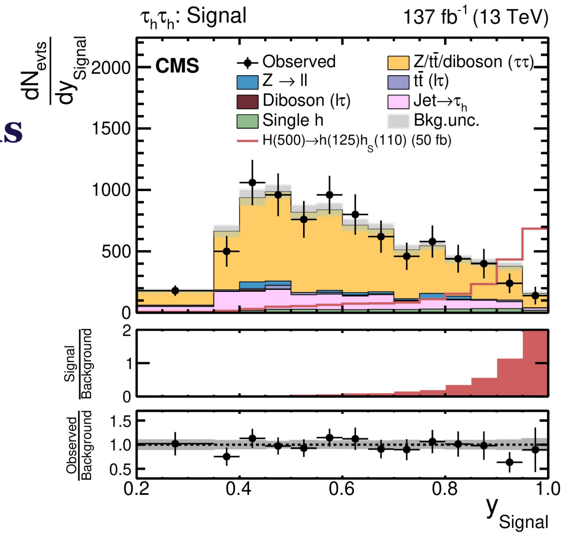
- **Model A:**
  - Prefer coupling to fermions
- **Model B:**
  - Prefer coupling to bosons
- **Model C:**
  - Fermiophobic

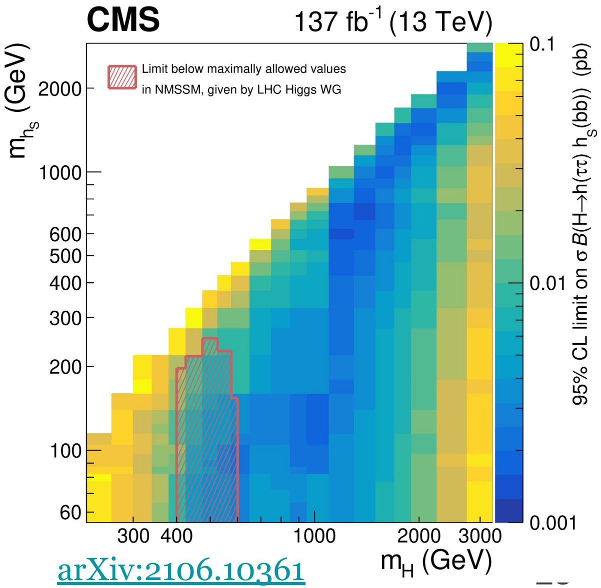
Search for resonances in $H \rightarrow hh_S \rightarrow bb\tau\tau$ decays:

- **Search for resolved $bbe\tau_h$, $bb\mu\tau_h$ and $bb\tau_h\tau_h$ final states**
- **Analysis strategy:**
  - Event categorisation based on neural networks (with five output nodes):
    - Events with true τ-pairs
    - Events with quark/gluon jets misidentified as τ_h
    - Top quark pair events
    - Remaining backgrounds
    - Signal events
  - **Fit all $\max(y_i)$ distributions**
    - 15 event categories



Predicted in e.g. NMSSM

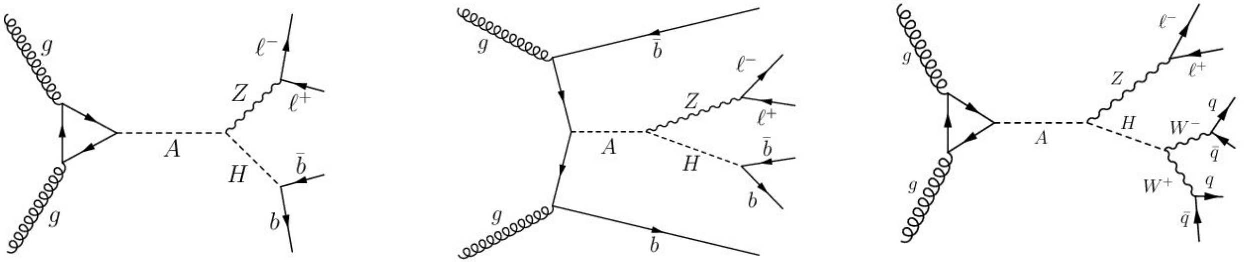


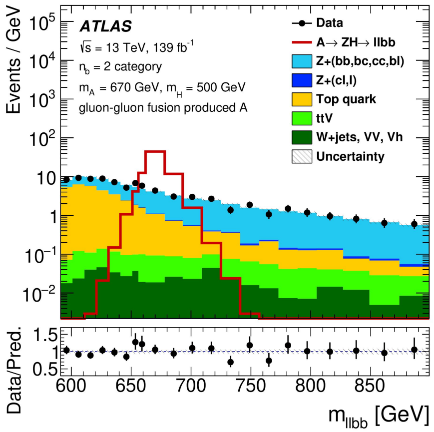


- **Dominant systematic uncertainties:**
  - Background modelling

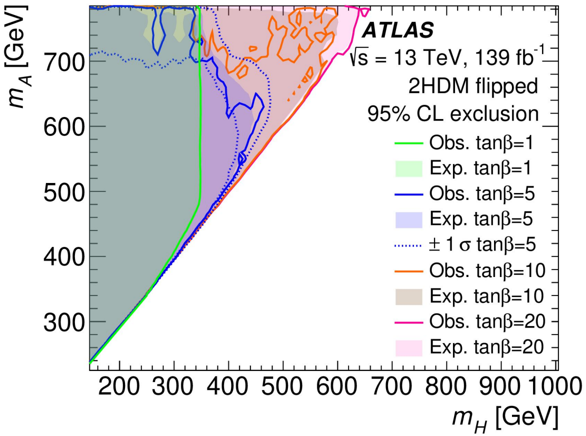
arXiv:2106.10361

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





- **Search for a new 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 syst. uncertainties:**
  - Data statistics
  - JES/JER

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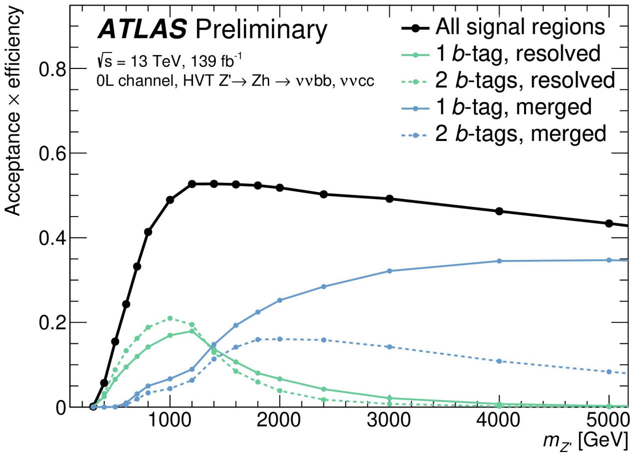
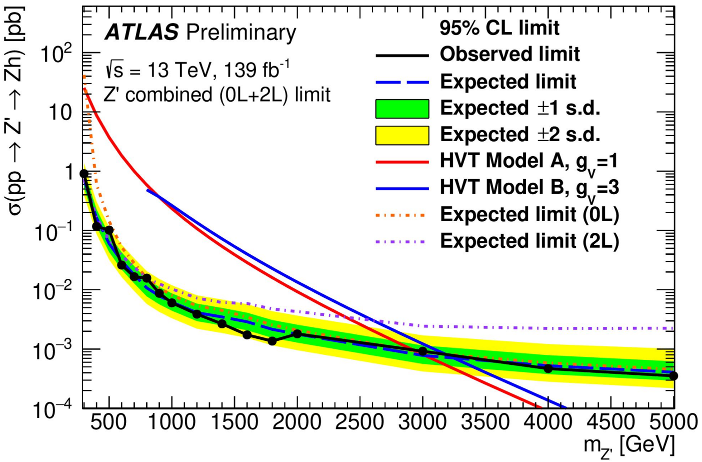
Search for resonances in X → Zh decays:

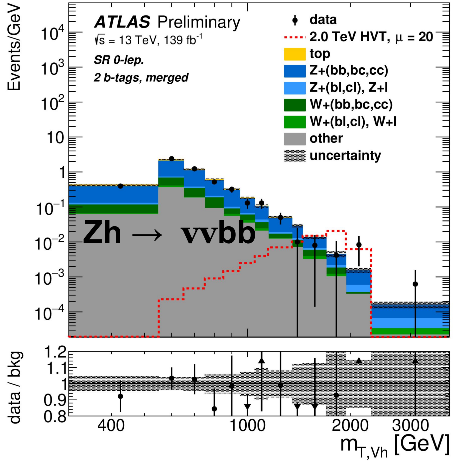
- **Probe resolved and merged νvbb and ℓℓbb (ℓ = μ,e) final states**
- **Analysis strategy:**
  - Search for bumps in m_T or $m_{\ell\ell bb}$ spectra:

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

  - Simultaneous fit of all 4 event categories: (resolved, merged) × (1-tag, 2-tag)
- **Dominant systematic uncertainties:**
  - Modelling of backgrounds (top bkg. ME +PS)
  - Large-R jets (mass resolution)







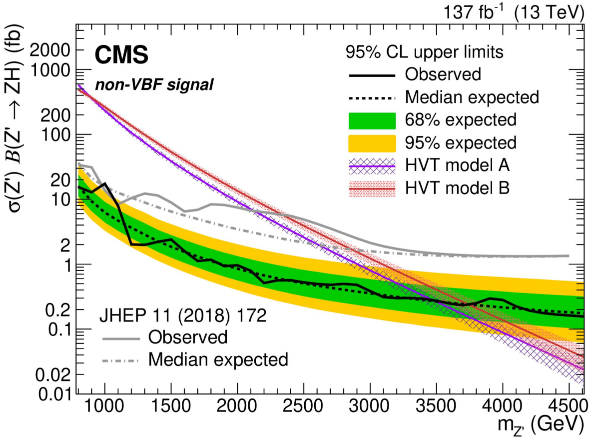
ATLAS-CONF-2020-043

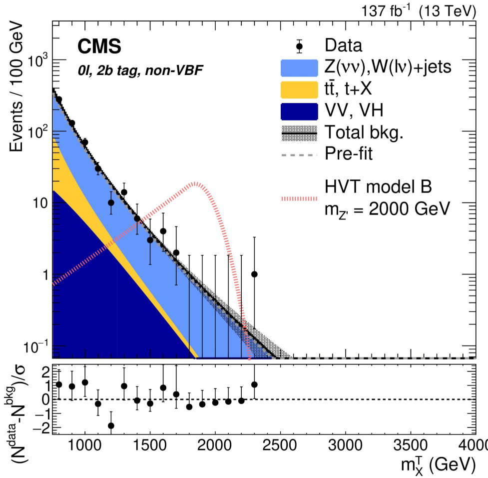
Search for resonances in X → Zh decays:

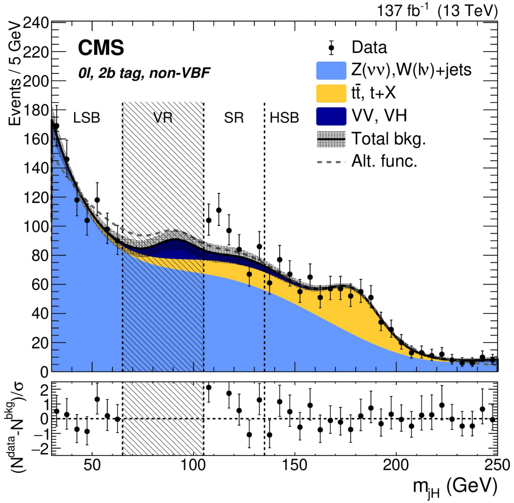
- **Probe merged ννbb and ℓℓbb (ℓ = μ, e) final states**
- **Analysis strategy:**
  - Backgrounds (V+ jets, top quark production, and VV/VH) are described by analytical functions

$$N_{\mathrm{SR}}^{\mathrm{V+jets}}(m) = \left[N_{\mathrm{SB}}^{\mathrm{data}}(m) - N_{\mathrm{SB}}^{\mathrm{top}}(m) - N_{\mathrm{SB}}^{\mathrm{VV}}(m)\right]\alpha(m) \quad \text{with:} \quad \alpha(m) = \frac{N_{\mathrm{SR}}^{\mathrm{V+jets}}(m)}{N_{\mathrm{SB}}^{\mathrm{V+jets}}(m)}$$

  - Search for bumps in m_T and $m_{\ell\ell bb}$ spectra
  - Simultaneous fit of all 6 event categories:
    - (νν, μμ, ee) × (1-tag, 2-tag)



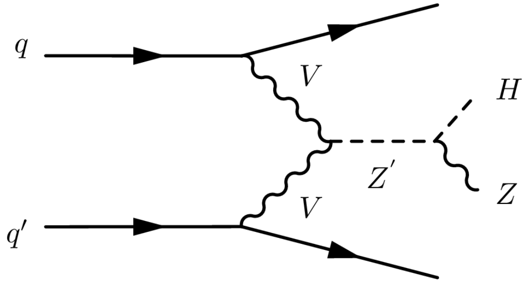


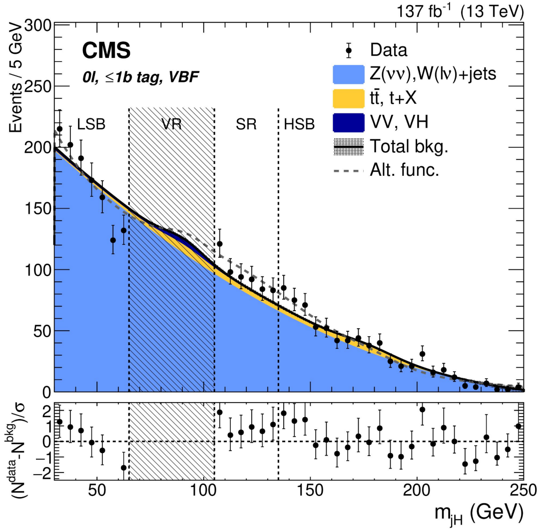


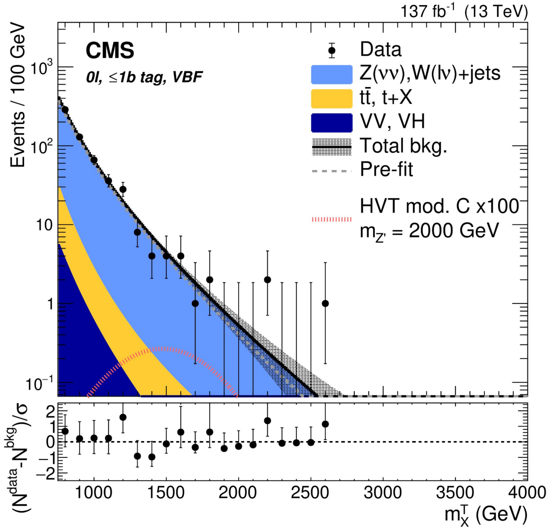
Eur. Phys. J. C 81 (2021) 688

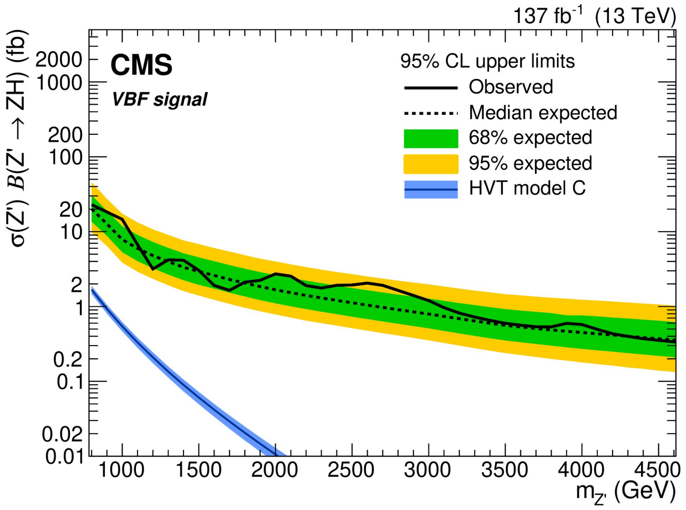
Search for resonances in X → Zh decays:

- **Probe merged vvbbjj and ℓℓbbjj (ℓ = μ, e) final states**
- Use same analysis strategy as non-VBF analysis
- Not sensitive **yet** to **Model C** of Heavy Vector Triplets









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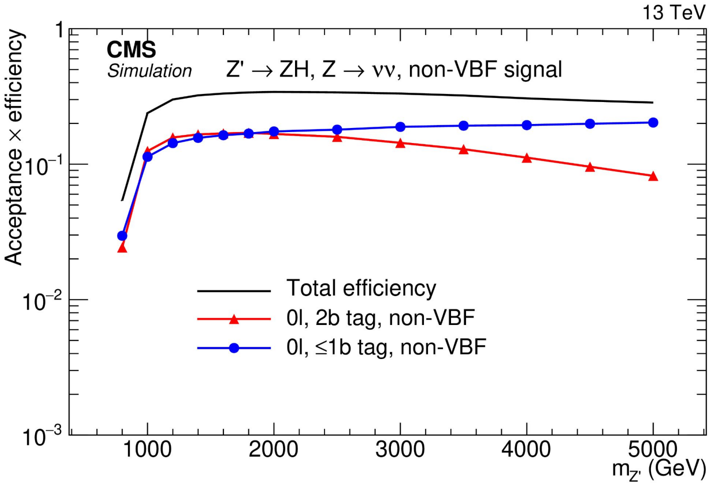
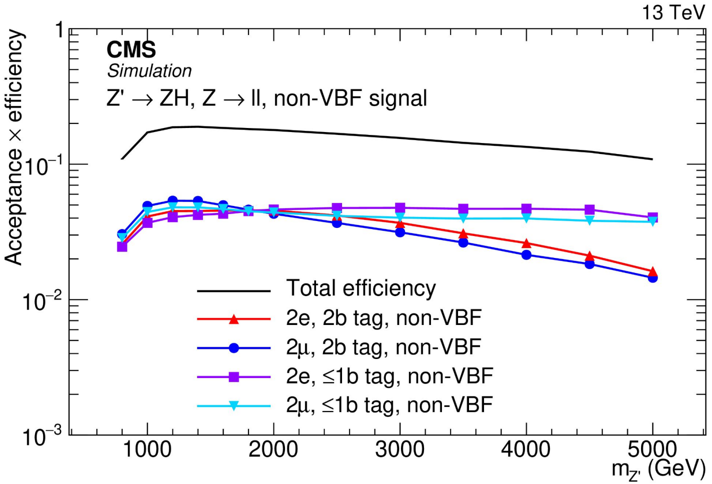
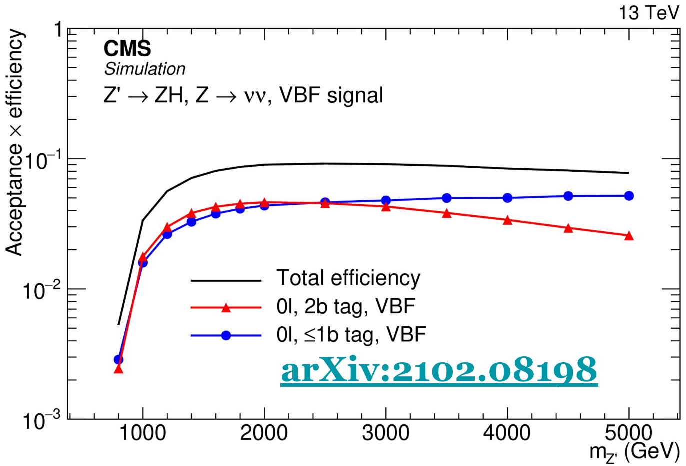
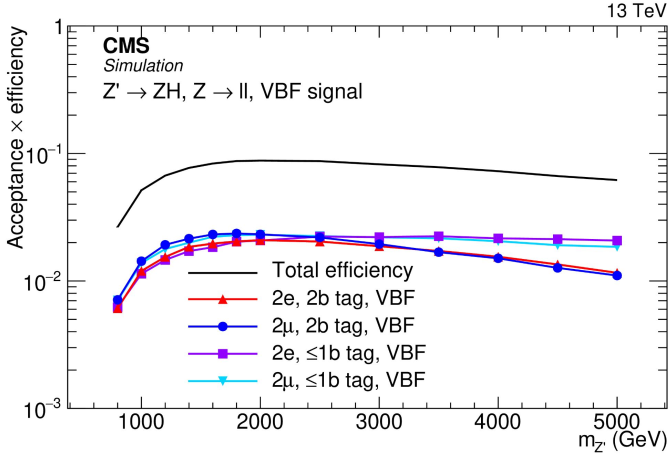
Search for resonances in X → Zh decays:



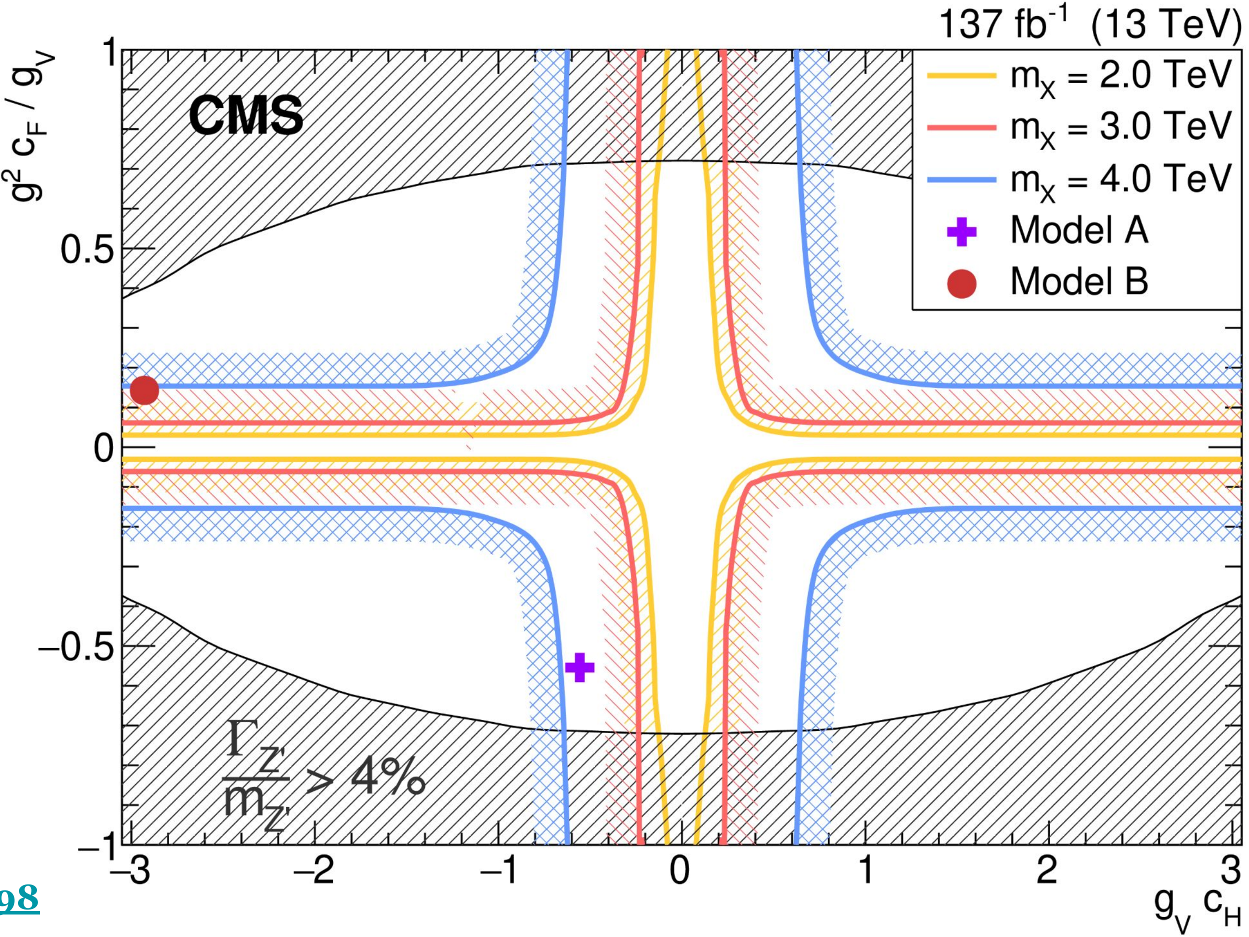




arXiv:2102.08198



Search for resonances in $X \to Zh$ decays:

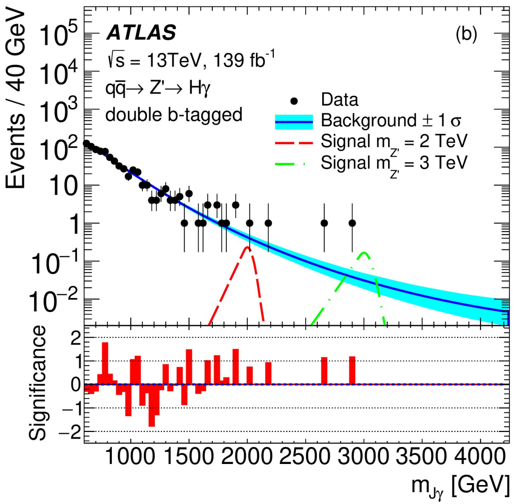


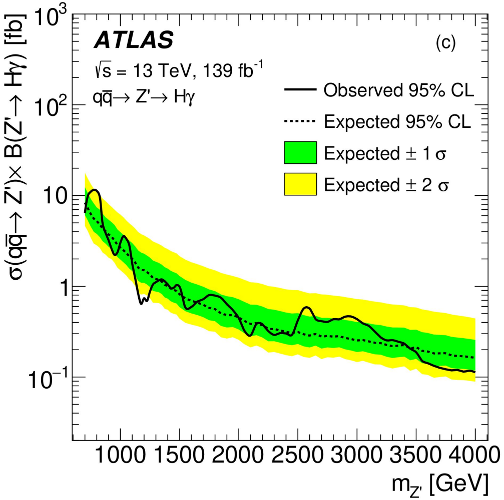
arXiv:2102.08198

Search for hγ resonances:

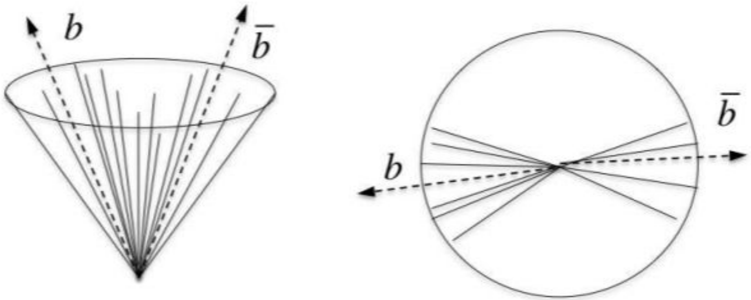
- **Search for hγ resonances in merged bbγ final state**
  - Hunt for bump in $m_{bb\gamma}$ spectrum covering mass range between 0.7 and 4 TeV
    - Use parametric fit function to describe background (smoothly falling)
    - The signal is modeled as a sum of a Crystal Ball function and a Gaussian
    - Use generic spin 1 ($qq \rightarrow Z' \rightarrow h\gamma$) 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



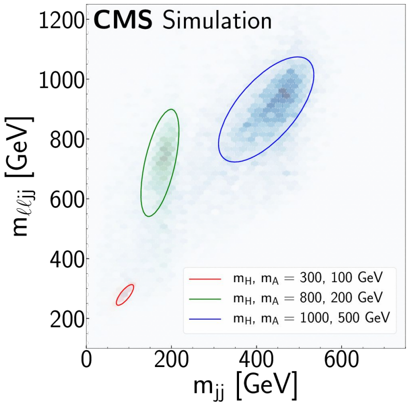
arXiv:1507.06913

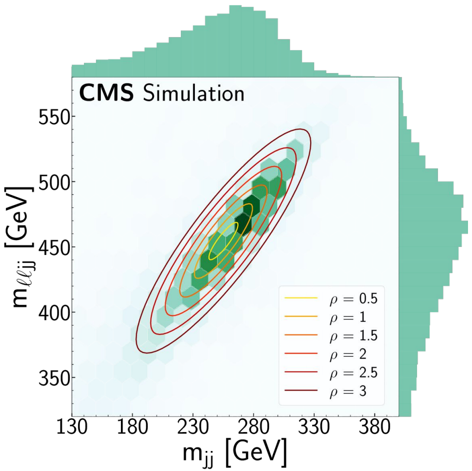
Search for new neutral Higgs bosons decaying via H→ZA or A → ZH:

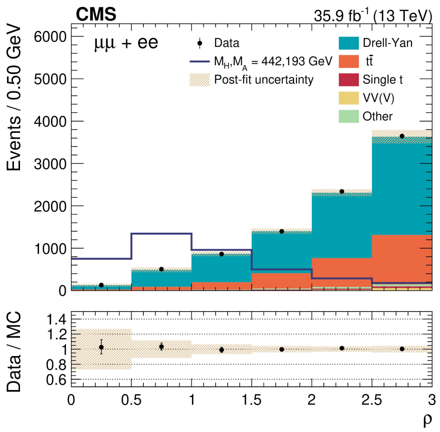
- **Probe ℓℓbb (ℓ = μ,e) final states**
- **Analysis strategy:**
  - Probe m_{jj} and $m_{\ell\ell bb}$ distributions for bumps within elliptical SRs
    - Size of ellipsoids depend on resonance masses (due to JER)
  - Transform 2D mass distribution into 1D distribution ρ:
    - Value of ρ depends on 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%)

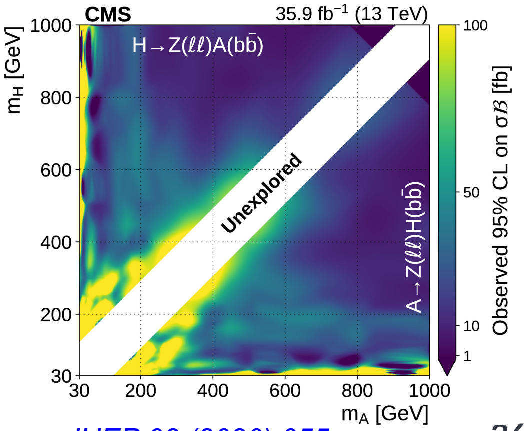
for $m_H \neq 125$ GeV

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









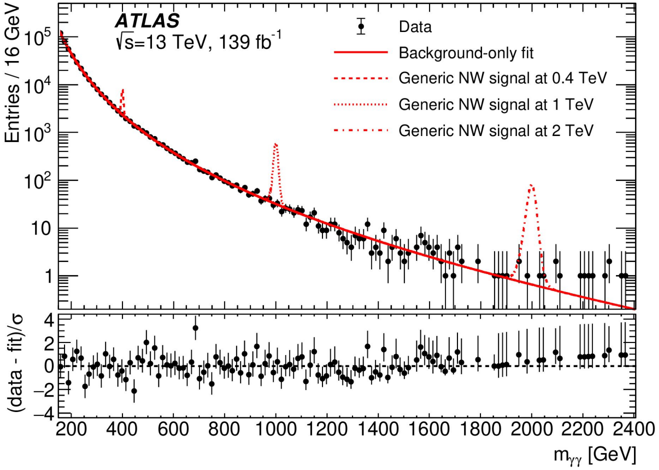
JHEP 03 (2020) 055

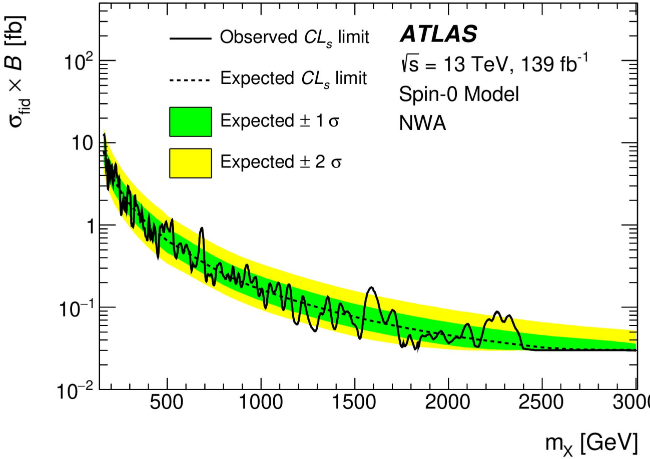
Search for a heavy resonance decaying to γγ:

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

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

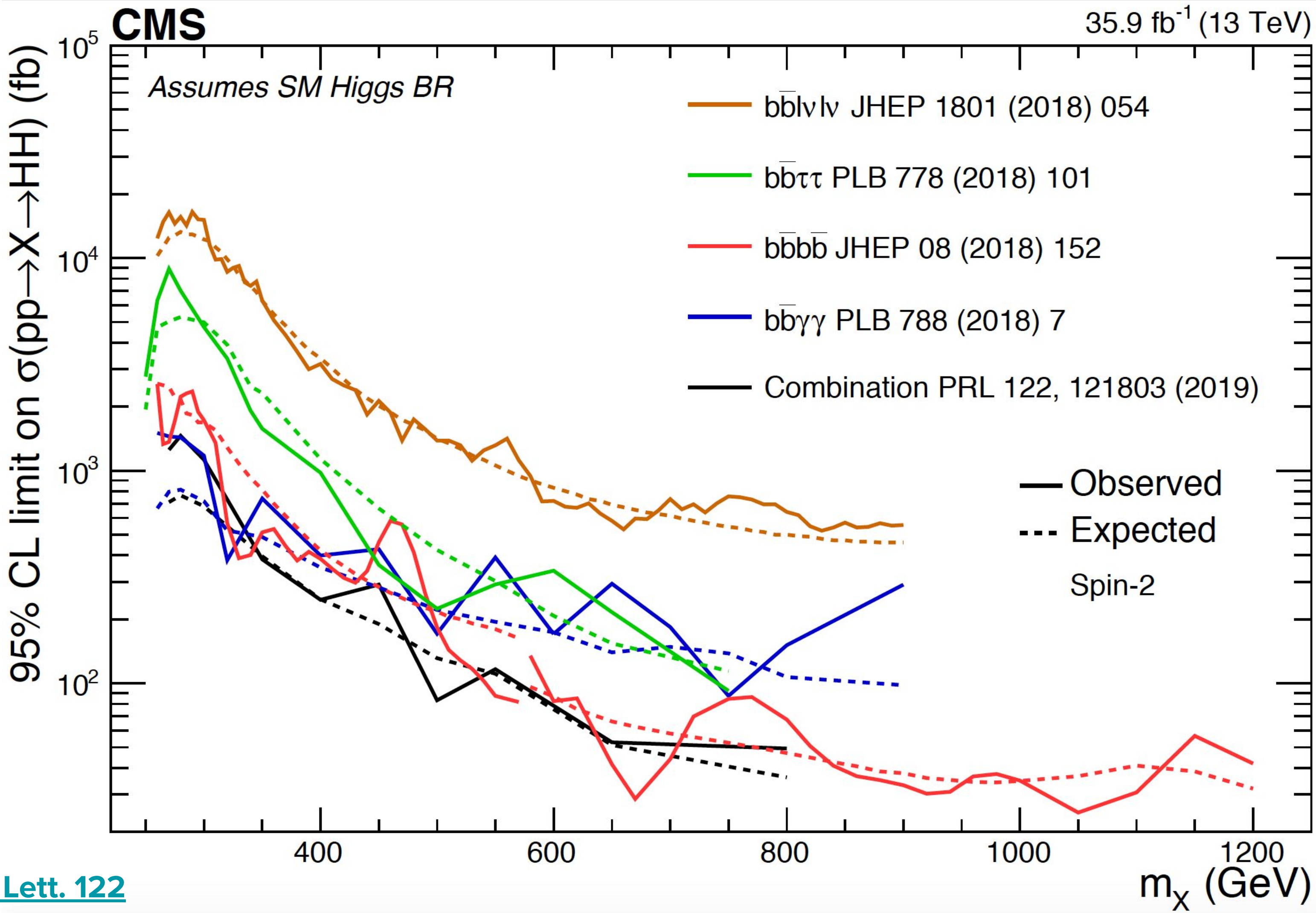
- **Dominant uncertainties:**
  - Spurious signal estimation
  - Photon energy resolution





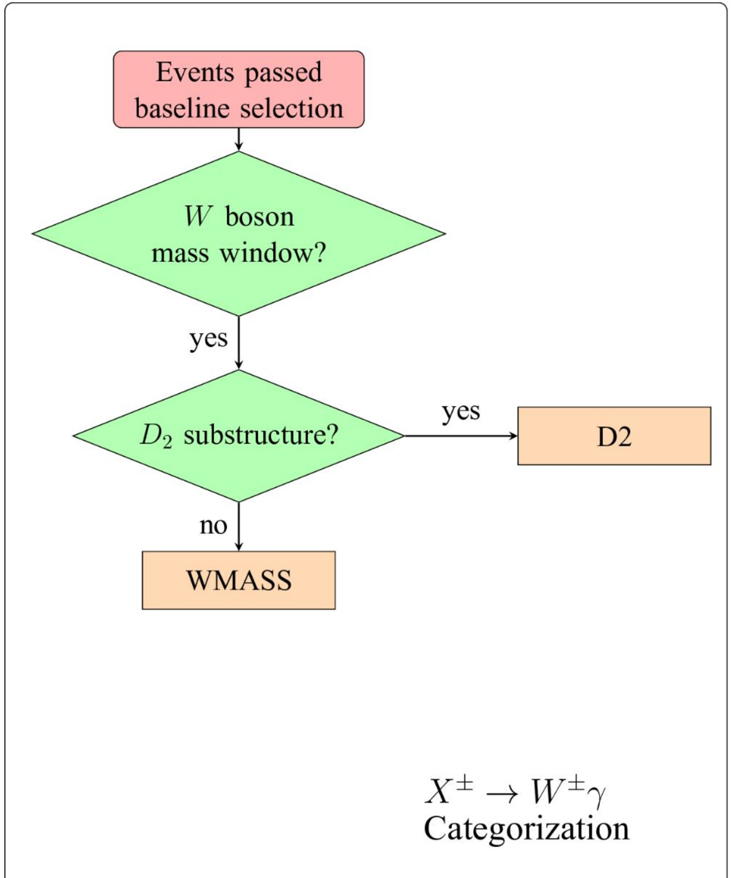
Largest local (global) deviation wrt SM expectations was found to be 3.3σ (1.3σ) for a mass around 680 GeV

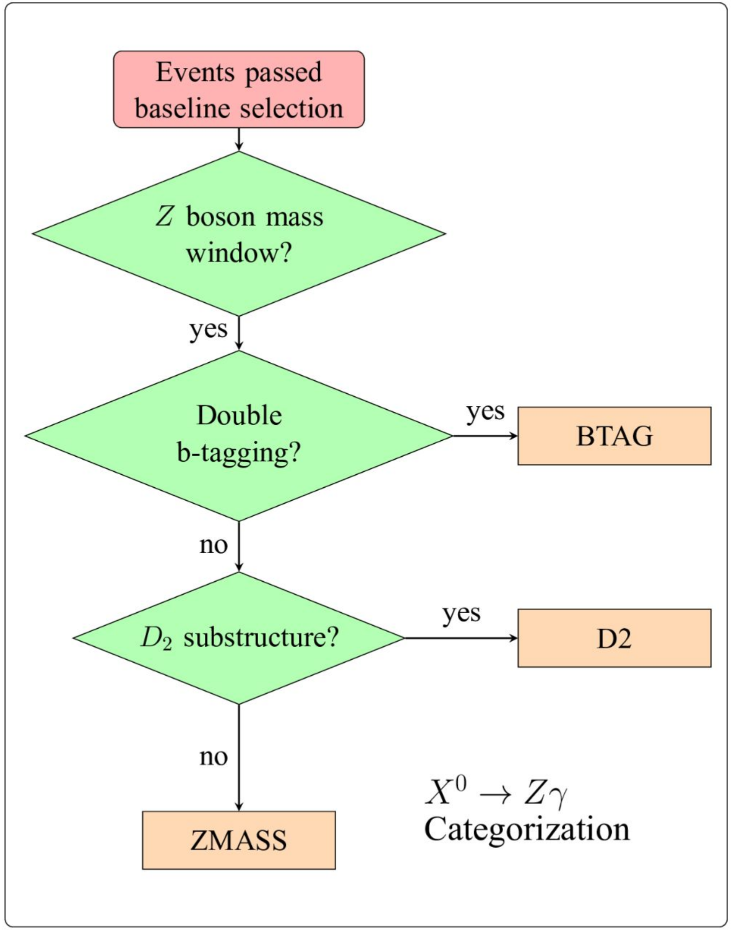
arXiv:2102.13405



Phys. Rev. Lett. 122

Search for high-mass $W\gamma$ and $Z\gamma$ resonances

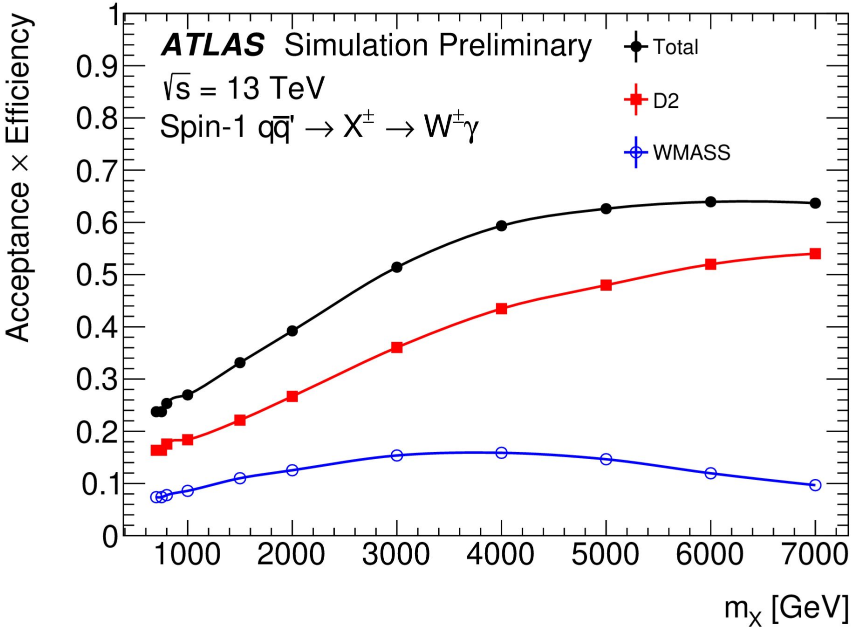


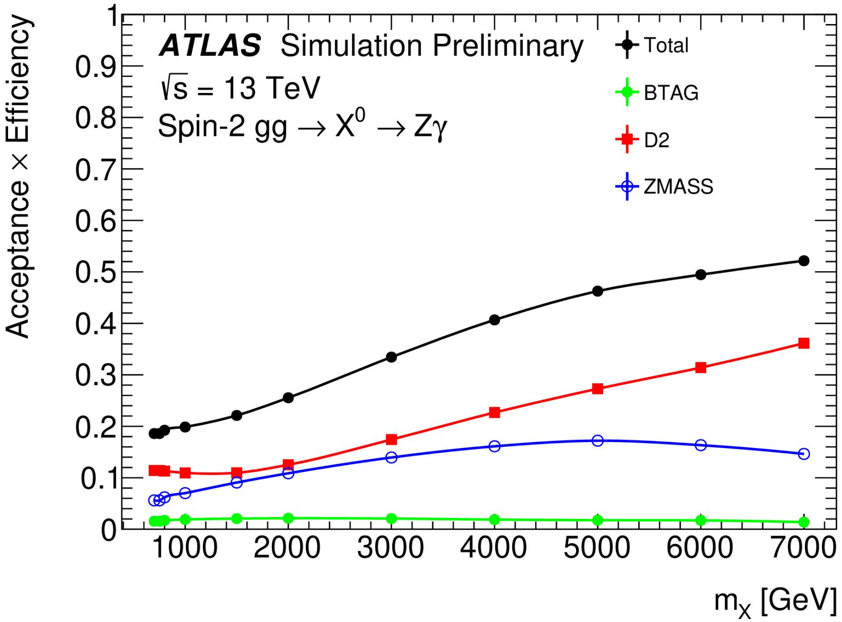


ATLAS-CONF-2021-041

Search for high-mass $W\gamma$ and $Z\gamma$ resonances

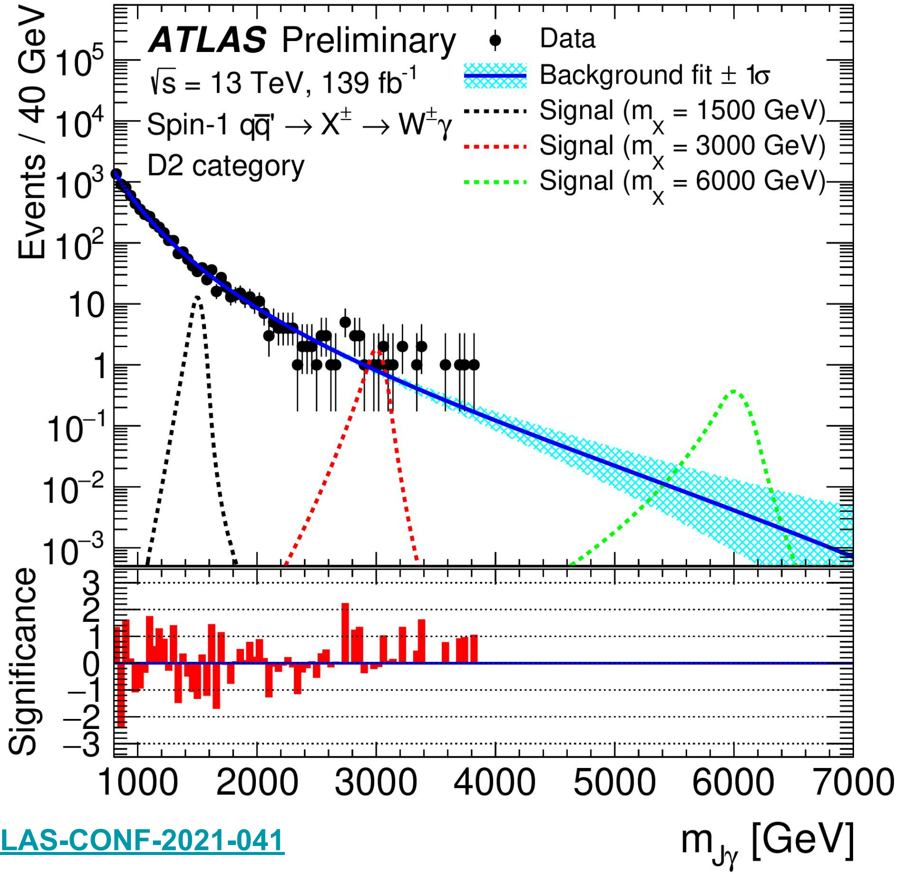
ATLAS-CONF-2021-041

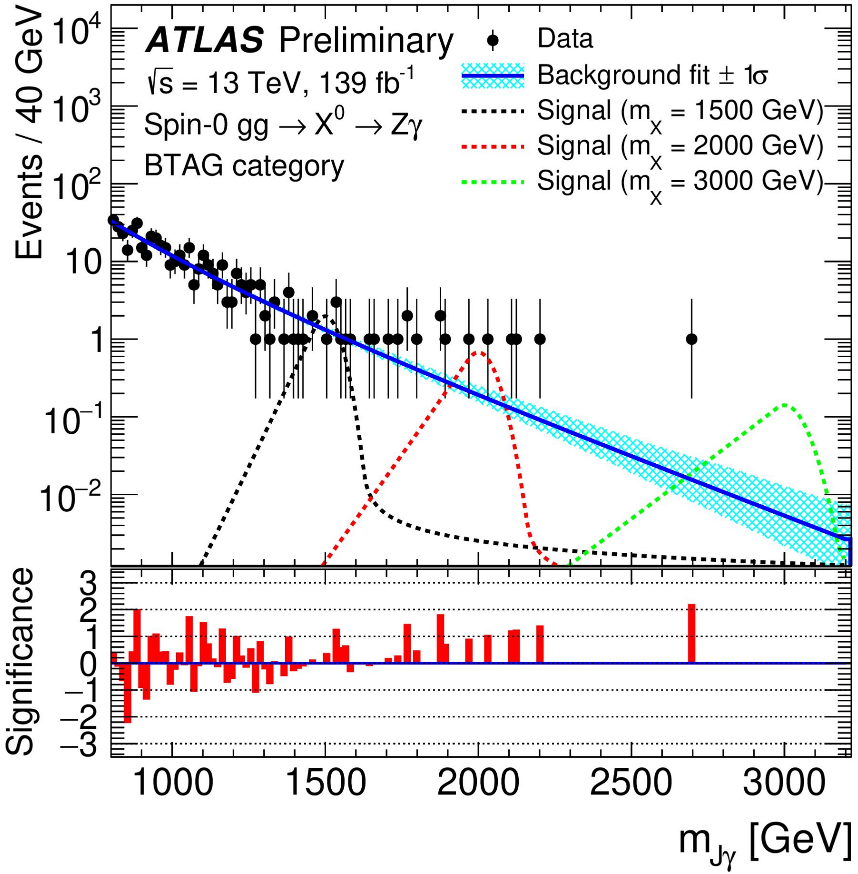




Efficiencies for the selection of signal events after categorization and application of the tighter photon E_T^{γ} selection used to optimize the signal significance

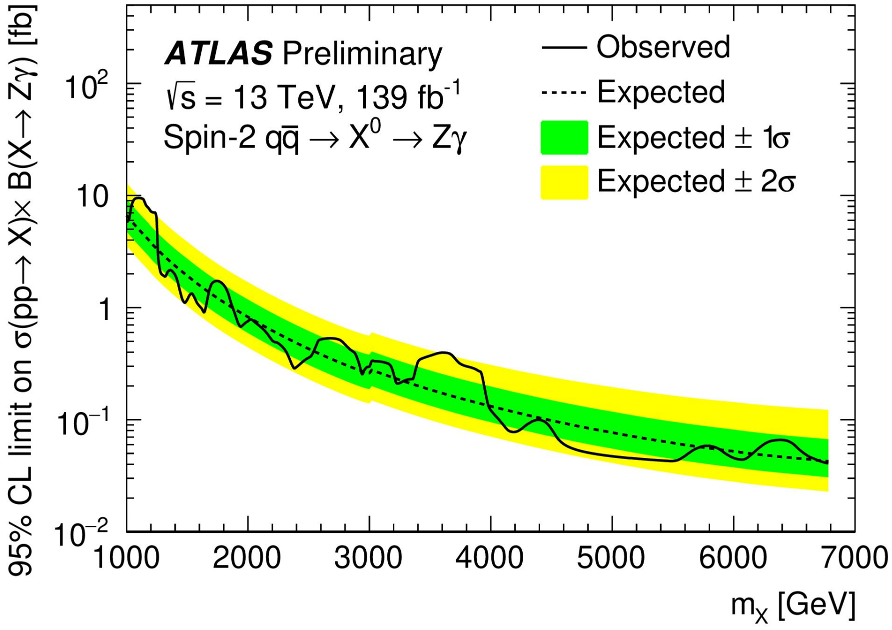
Search for high-mass *Wγ* and *Zγ* resonances

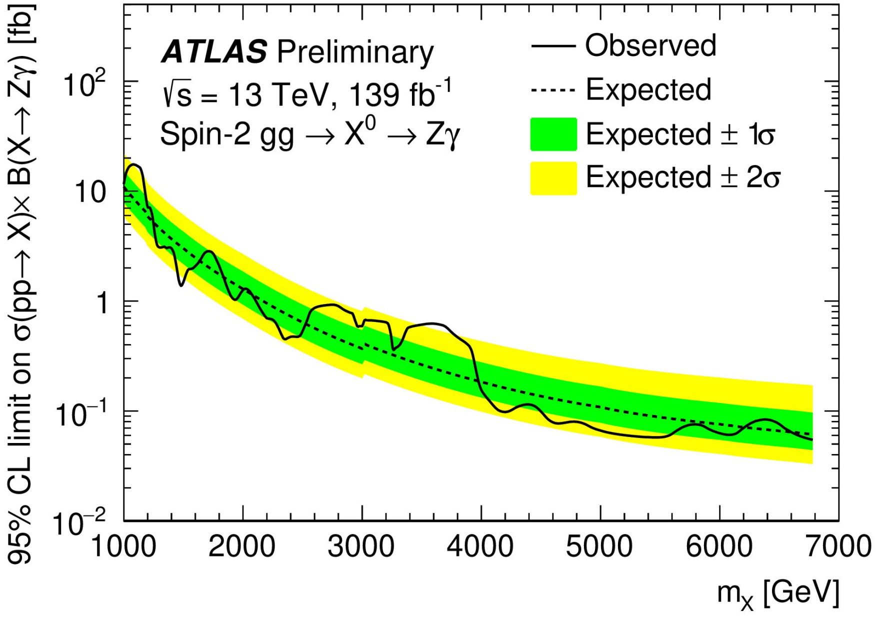




ATLAS-CONF-2021-041

Search for high-mass *Wγ* and *Zγ* resonances





ATLAS-CONF-2021-041

Search for new particles in X → ZZ, ZH, ZW events:

CMS-PAS-B2G-20-013

Source	Boosted Background	Boosted Signal	Resolved Background	Resolved Signal
Integrated luminosity	1.8		1.8	
Electron trigger and ID	2.0		2.0	
Muon trigger and ID	1.5		1.5	
Electron energy scale	0.8	<0.1–0.2	0.9	<0.1
Muon momentum scale	0.5	<0.1–0.1	0.6	<0.1
Jet energy scale	1.0	<0.1–0.1	2.8	0.1–1.9
Jet energy resolution	0.3	<0.1–0.3	0.3	1.0
b tag SF untagged	0.1	1.0–7.4	0.1	0.7–2.2
b tag SF tagged	12	12	3.6	4
Mistag SF untagged	0.3	<0.1–0.2	0.2	0.1
Mistag SF tagged	3.5	0.1–0.3	3.8	0.4–1.0
SM ZV production	12	—	12	—
t + X normalization	4 (eμ)	—	4 (eμ)	—
V identification (τ_{21})	5 (ZV)	5	—	—
V identification (extrap.)	—	2.6–6.0	—	—
V mass scale	0.6 (ZV)	0.4–0.8	—	—
V mass resolution	5.0 (ZV)	5.0–6.0	—	—
Pileup	0.5	0.1–0.2	0.1	0.1–0.2
SR-to-SB norm. ratio	3 (Z + jets)	—	5 (Z + jets)	—
PDFs	—	1.5–1.6	—	0.3–1.1
QCD renorm./fact. scales	—	0.1–0.3	—	0.2–0.3

Summary of systematic uncertainties, quoted in percent, affecting the normalization of background and signal samples. Where a systematic uncertainty depends on the signal ZV or ZH final state or mass, the smallest and largest values are reported in the table. In the case of a systematic uncertainty applying only to a specific background source, the source is indicated in parentheses.

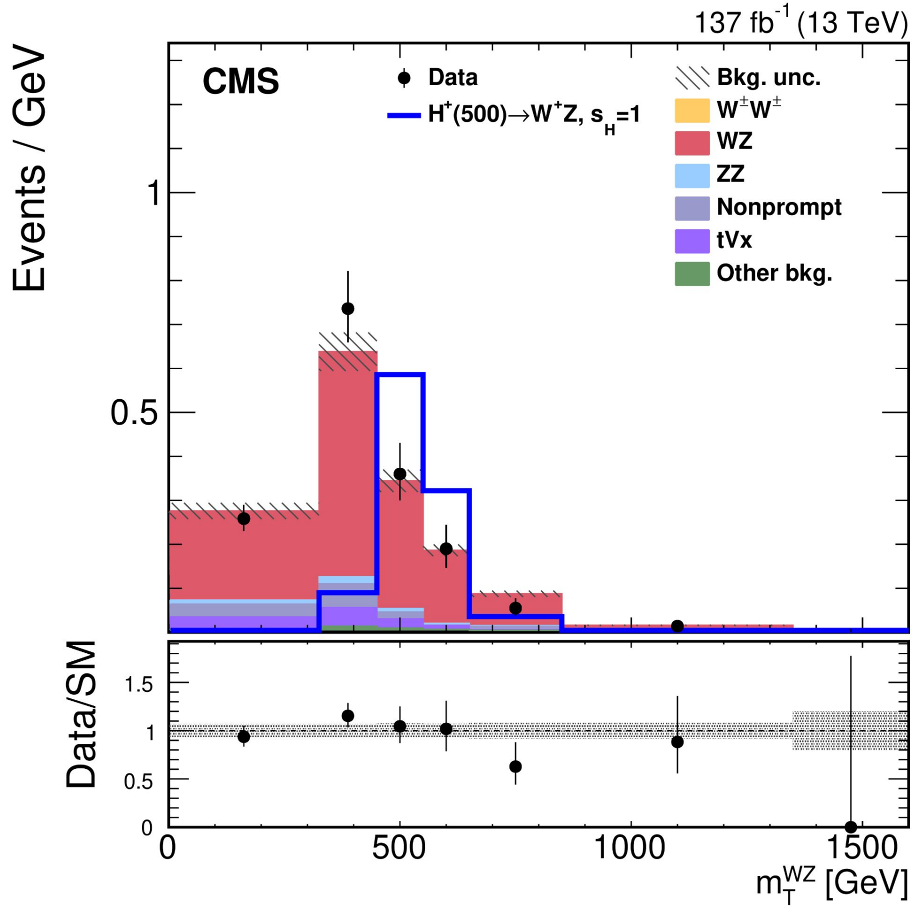
Search for leptophobic charged Higgs bosons:

Summary of the event selection requirements for the $W^{\pm}W^{\pm}$ and WZ signal regions. The looser lepton p_T requirement in the WZ selection refers to the trailing lepton from the Z boson decays. The $|m_{\ell\ell} - m_Z|$ requirement is applied only to the dielectron final state in the $W^{\pm}W^{\pm}$ SR.

arXiv:2104.04762

Variable	$W^{\pm}W^{\pm}$	WZ
Leptons	2 leptons, $p_T > 25/20$ GeV	3 leptons, $p_T > 25/10/20$ GeV
p_T^j	$>50/30$ GeV	$>50/30$ GeV
$\lvert m_{\ell\ell} - m_Z \rvert$	>15 GeV (ee)	<15 GeV
$m_{\ell\ell}$	>20 GeV	—
$m_{\ell\ell\ell}$	—	>100 GeV
p_T^{miss}	>30 GeV	>30 GeV
b jet veto	Required	Required
τ_h veto	Required	Required
$\max(z_\ell^*)$	<0.75	<1.0
m_{jj}	>500 GeV	>500 GeV
$\lvert \Delta\eta_{jj} \rvert$	>2.5	>2.5

Search for leptophobic charged Higgs bosons:



arXiv:2104.04762

Summary of the impact of the systematic uncertainties on the extracted signal strength for a background-only fits

Source of uncertainty	$\Delta\mu$ background-only	$\Delta\mu$ $s_H = 1.0$ and $m_{H_5} = 500\,\text{GeV}$
Integrated luminosity	0.002	0.019
Pileup	0.001	0.001
Lepton measurement	0.003	0.033
Trigger	0.001	0.007
JES and JER	0.003	0.006
btagging	0.001	0.006
Nonprompt rate	0.002	0.002
$W^{\pm}W^{\pm}$/WZ rate	0.014	0.015
Other prompt background rate	0.002	0.015
Signal rate	—	0.064
Simulated sample size	0.005	0.005
Total systematic uncertainty	0.016	0.078
Statistical uncertainty	0.021	0.044
Total uncertainty	0.027	0.090

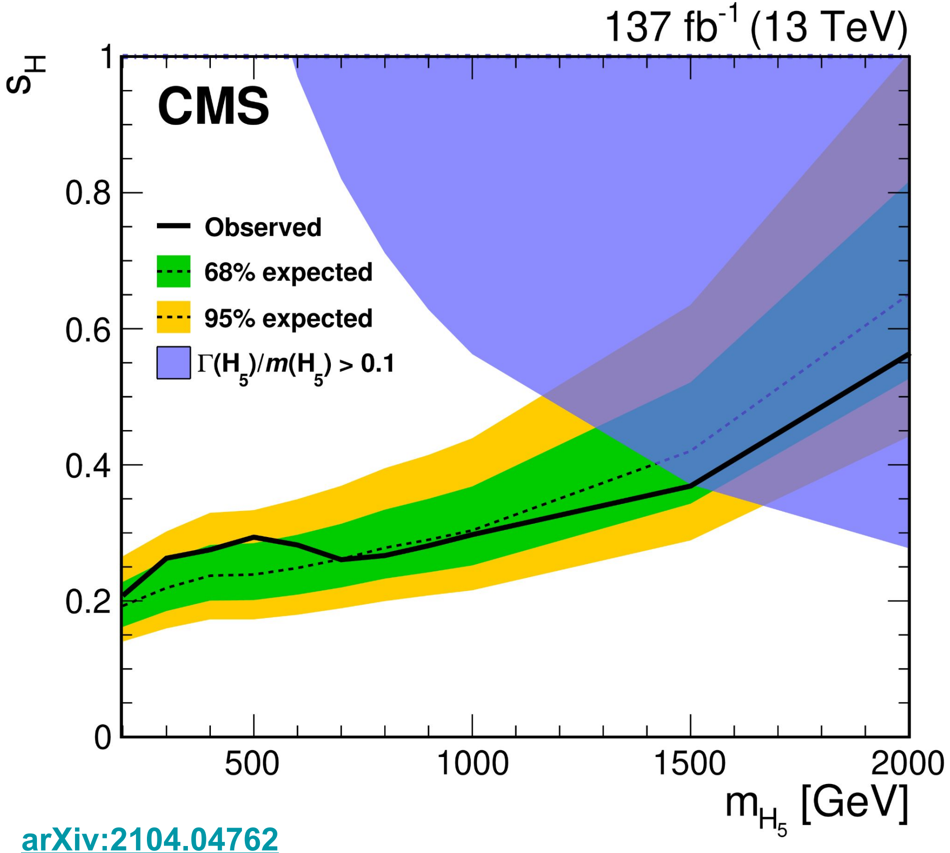
Search for leptophobic charged Higgs bosons:

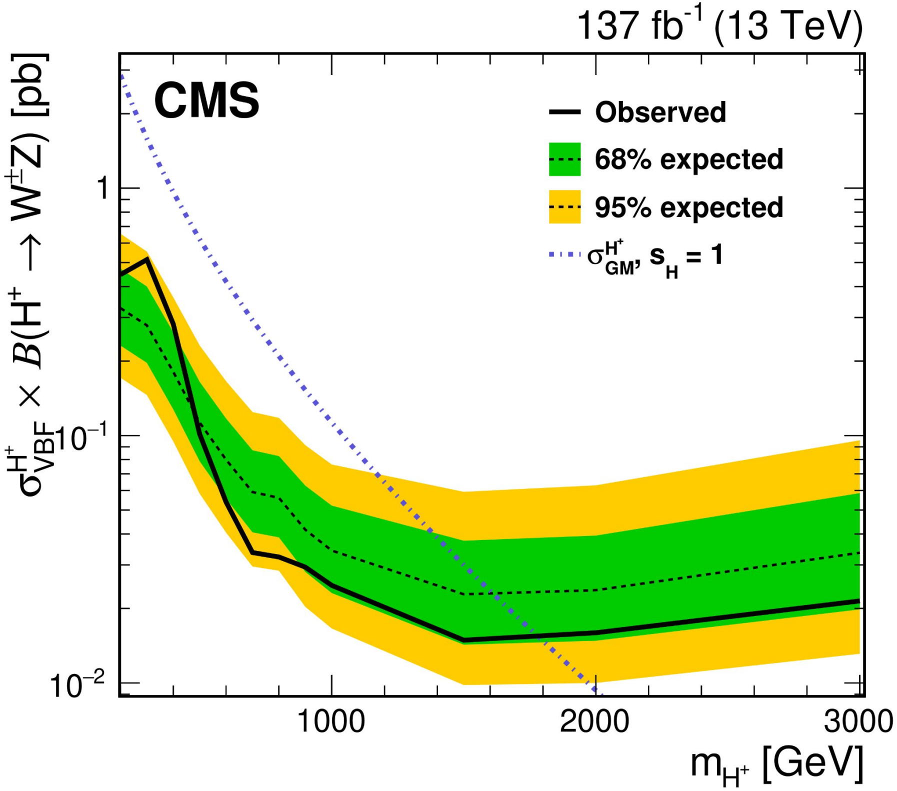
Expected signal and background yields from various SM processes and observed data events in all regions used in the analysis. The expected background yields are shown with their normalisations from the simultaneous fit for the background-only hypothesis

arXiv:2104.04762

Process	WW SR	WZ SR	Nonprompt CR	tZq CR	ZZ CR
$H^{\pm\pm}(500) \to W^{\pm}W^{\pm}$	666 ± 68	—	48.9 ± 5.1	—	—
$H^{\pm}(500) \to WZ$	19.2 ± 2.4	107 ± 11	1.7 ± 0.2	8.0 ± 0.9	—
$W^{\pm}W^{\pm}$	230 ± 16	—	28.2 ± 1.8	—	—
WZ	67.8 ± 5.8	196 ± 15	10.3 ± 1.0	27.2 ± 2.4	—
ZZ	0.7 ± 0.2	6.4 ± 2.0	0.1 ± 0.1	1.1 ± 0.3	13.3 ± 4.0
Nonprompt	262 ± 36	22.3 ± 7.7	263 ± 21	8.4 ± 3.1	0.2 ± 0.2
tVx	8.4 ± 1.9	17.7 ± 3.3	28.8 ± 5.6	62 ± 11	0.2 ± 0.1
Other background	31.1 ± 7.3	6.8 ± 1.4	21.1 ± 4.2	2.2 ± 0.4	0.3 ± 0.1
Total background	600 ± 40	249 ± 18	352 ± 22	101 ± 12	14.0 ± 4.0
Data	602	249	352	101	14

Search for leptophobic charged Higgs bosons:





arXiv:2104.04762

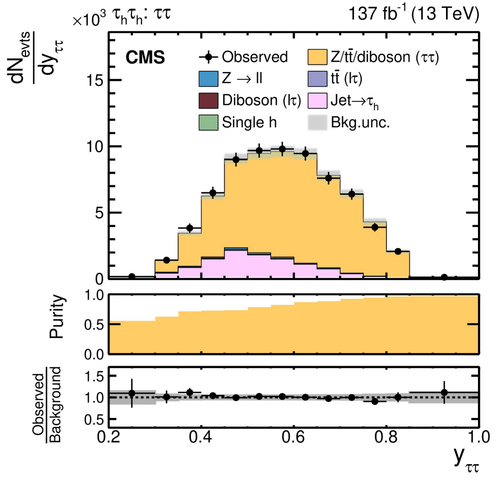
Search for resonances in $X \to hh_s \to bb\tau\tau$ decays:

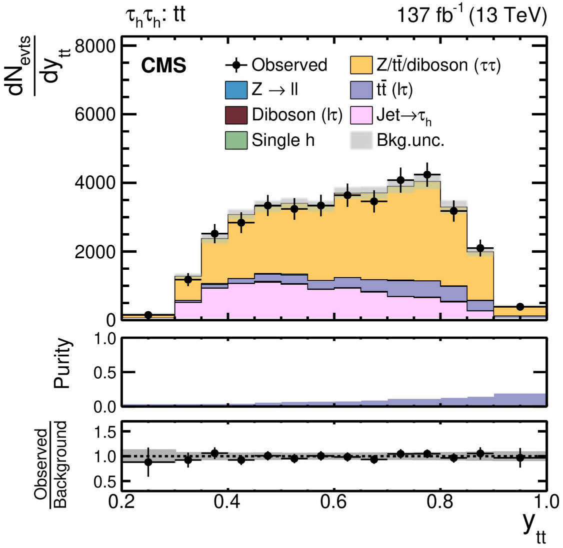
Offline requirements applied to electrons, muons, and τ_h candidates used for the selection of the $\tau\tau$ pair. The p_T values in parentheses correspond to events selected by a single-electron or single-muon trigger. These requirements depend on the year of data-taking. For D_{jet} the efficiency and for $De(\mu)$ the misidentification rates for the chosen working points are given in parentheses.

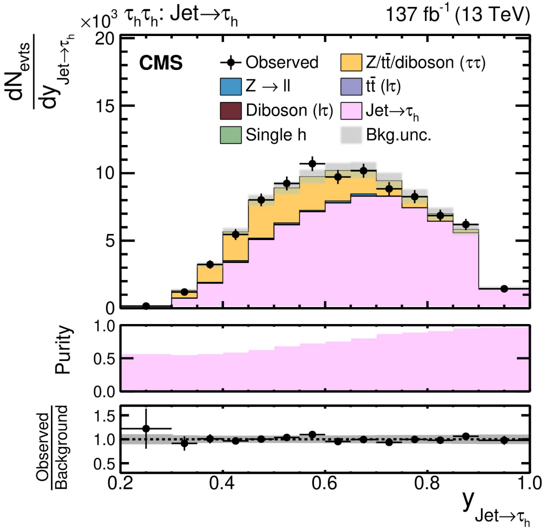
Final state	Electron/Muon	τ_h
$e\tau_h$	$p_T > 25\,(26, 28, 33)$ GeV	$p_T > 35\,(30)$ GeV
	$\lvert\eta\rvert < 2.1$	$\lvert\eta\rvert < 2.3$
	$I^{e}_{rel} < 0.15$	$D_{jet}\,(70\%)$, $D_e\,(0.05\%)$, $D_\mu\,(0.13\%)$
$\mu\tau_h$	$p_T > 20\,(23, 25)$ GeV	$p_T > 35\,(30)$ GeV
	$\lvert\eta\rvert < 2.1$	$\lvert\eta\rvert < 2.3$
	$I^{\mu}_{rel} < 0.15$	$D_{jet}\,(70\%)$, $D_e\,(2.60\%)$, $D_\mu\,(0.03\%)$
$\tau_h\tau_h$	—	$p_T > 40$ GeV
		$\lvert\eta\rvert < 2.1$
		$D_{jet}\,(70\%)$, $D_e\,(2.60\%)$, $D_\mu\,(0.13\%)$

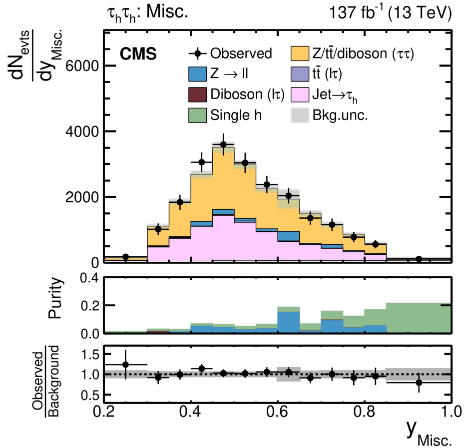
arXiv:2106.10361

Search for resonances in $X \rightarrow hh_S \rightarrow bb\tau\tau$ decays:





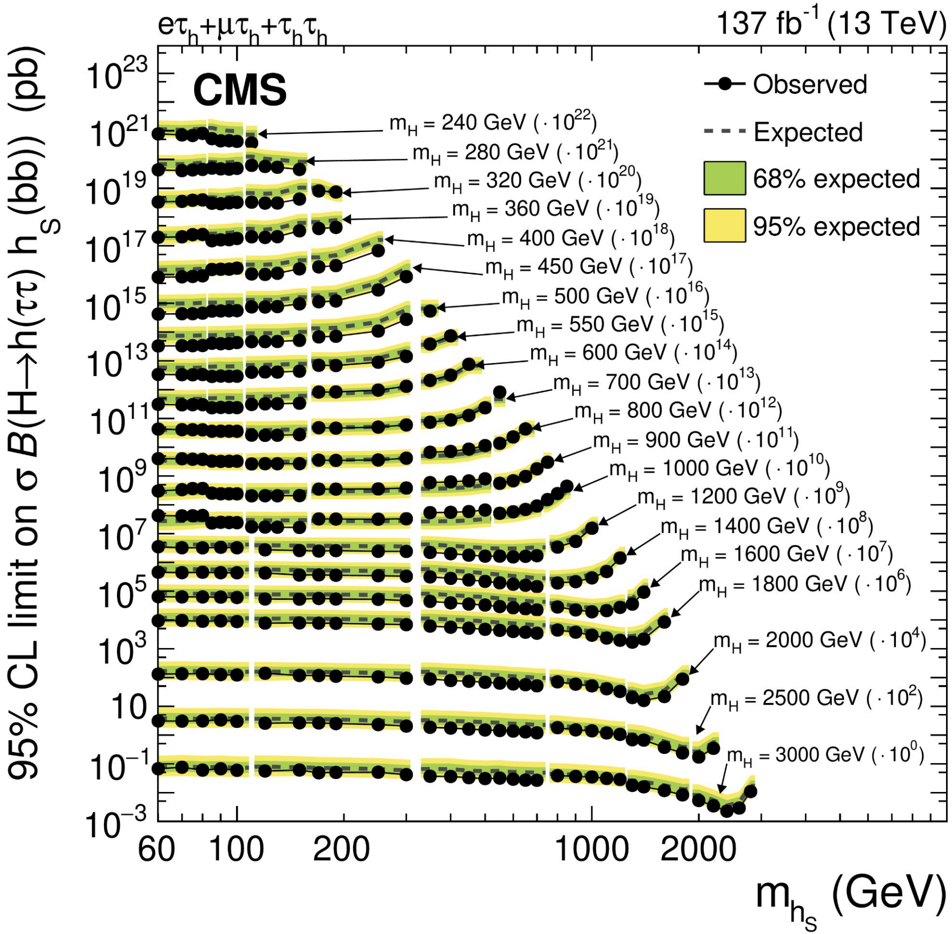




Shown is the signal category, obtained by NN classification based on a training for m_H = 500 GeV and 100 ≤ m_{hS} < 150 GeV in the $\tau_h\tau_h$ final state. The data sets of all years have been combined. The uncertainty bands correspond to the combination of statistical and systematic uncertainties after the fit to the signal plus background hypothesis for m_H = 500 GeV and m_{hS} = 110 GeV.

arXiv:2106.10361

Search for resonances in X → hh_S → bbττ decays:



Expected and observed 95% CL upper limits on σB(H→h(ττ)hS(bb)) for all tested values of m_H and m_{hS}. The limits for each corresponding mass value have been scaled by orders of ten as indicated in the annotations. Groups of hypothesis tests based on the same NN trainings for classification are indicated by discontinuities in the limits, which are linearly connected otherwise to improve the visibility of common trends.

arXiv:2106.10361

Search for doubly and singly charged Higgs bosons:

Charged Higgs boson mass	$m_{H^{\pm\pm}}$ = 200 GeV	$m_{H^{\pm\pm}}$ = 300 GeV	$m_{H^{\pm\pm}}$ = 400 GeV	$m_{H^{\pm\pm}}$ = 500 GeV
Selection criteria	$2\ell^{sc}$ channel			
m_{jets} [GeV]	[100, 450]	[100, 500]	[300, 700]	[400, 1000]
S	<0.3	<0.6	<0.6	<0.9
$\Delta R_{\ell^\pm\ell^\pm}$	<1.9	<2.1	<2.2	<2.4
$\Delta\phi_{\ell\ell,E_T^{miss}}$	<0.7	<0.9	<1.0	<1.0
$m_{x\ell}$ [GeV]	[40, 150]	[90, 240]	[130, 340]	[130, 400]
E_T^{miss} [GeV]	>100	>130	>170	>200
Selection criteria	3ℓ channel			
$\Delta R_{\ell^\pm\ell^\pm}$	[0.2, 1.7]	[0.0, 2.1]	[0.2, 2.5]	[0.3, 2.8]
$m_{x\ell}$ [GeV]	>160	>190	>240	>310
E_T^{miss} [GeV]	>30	>55	>80	>90
$\Delta R_{\ell jet}$	[0.1, 1.5]	[0.1, 2.0]	[0.1,2.3]	[0.5, 2.3]
$p_T^{leading\ jet}$ [GeV]	>40	>70	>100	>95
Selection criteria	4ℓ channel			
$m_{x\ell}$ [GeV]	>230	>270	>360	>440
E_T^{miss} [GeV]	>60	>60	>60	>60
$p_T^{\ell_1}$ [GeV]	>65	>80	>110	>130
$\Delta R_{\ell^\pm\ell^\pm}^{min}$	[0.2, 1.2]	[0.2, 2.0]	[0.5, 2.4]	[0.6, 2.4]
$\Delta R_{\ell^\pm\ell^\pm}^{max}$	[0.3, 2.0]	[0.5, 2.6]	[0.4, 3.1]	[0.6, 3.1]

Definition of the signal regions optimised for the study of different $H^{\pm\pm}$ and $H^{\pm}$ mass hypotheses. The selection is applied on top of the preselections. For the $H^{\pm\pm}$ pair production mode, the $m_H^{\pm\pm}$= 300 GeV signal regions are also used for $m_H^{\pm\pm}$= 350 GeV. For the $H^{\pm\pm}$ and $H^{\pm}$ associated production mode, the $m_H^{\pm\pm}$= 200 GeV, 400 GeV and 500 GeV signal regions are also used for $m_H^{\pm\pm}$= 220 GeV, 450 GeV and 550 GeV, respectively.

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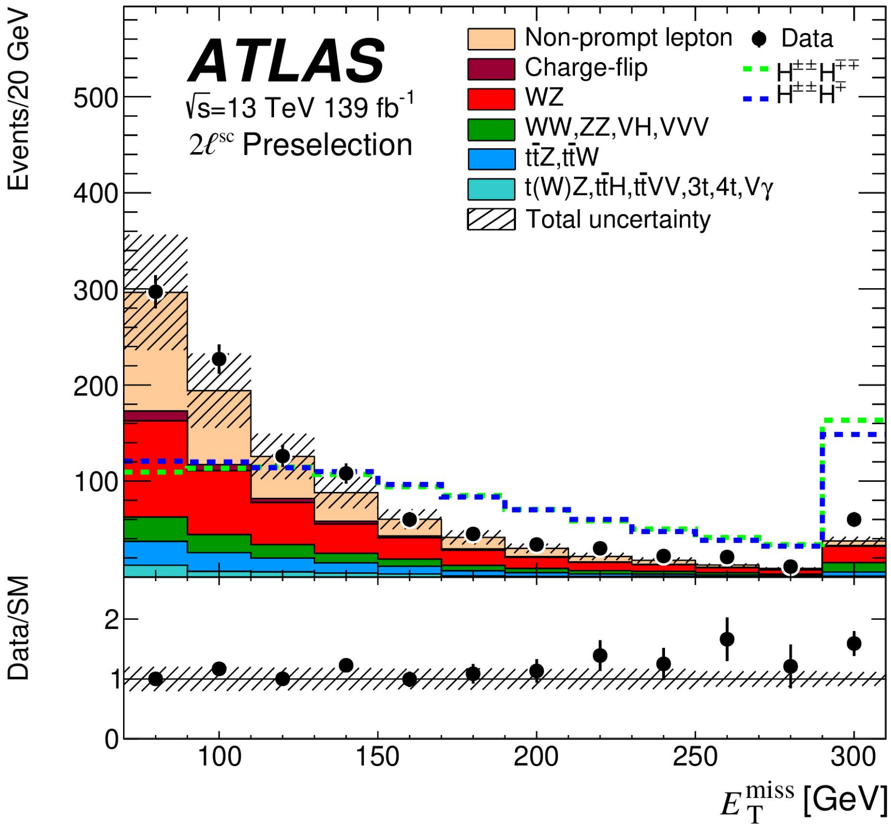
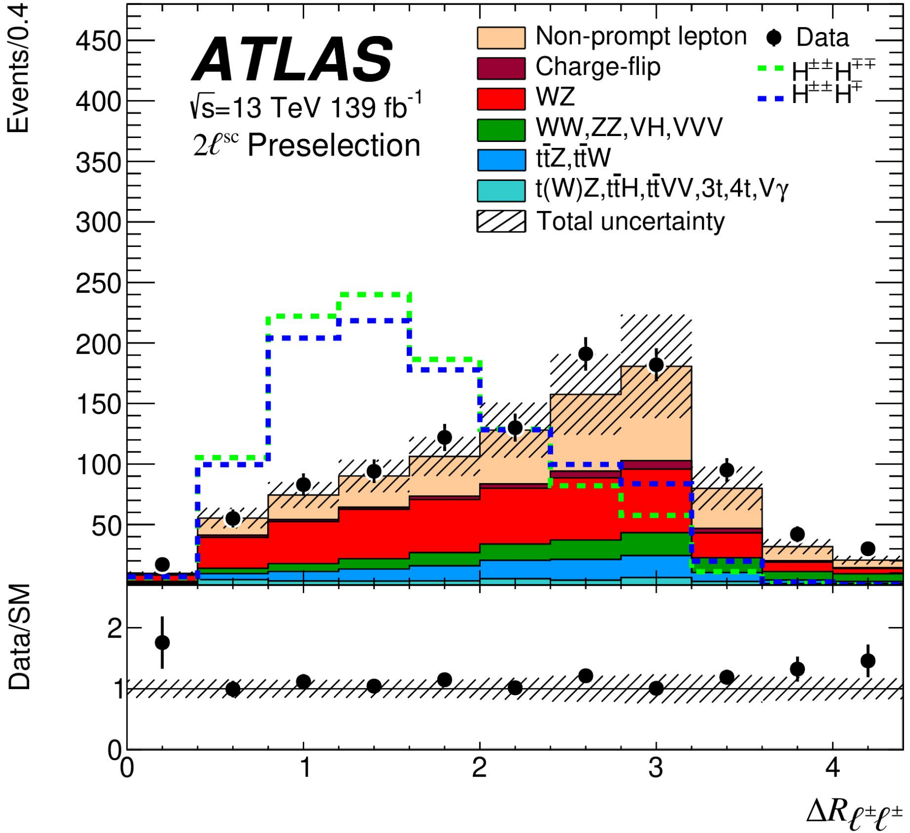
Search for doubly and singly charged Higgs bosons:





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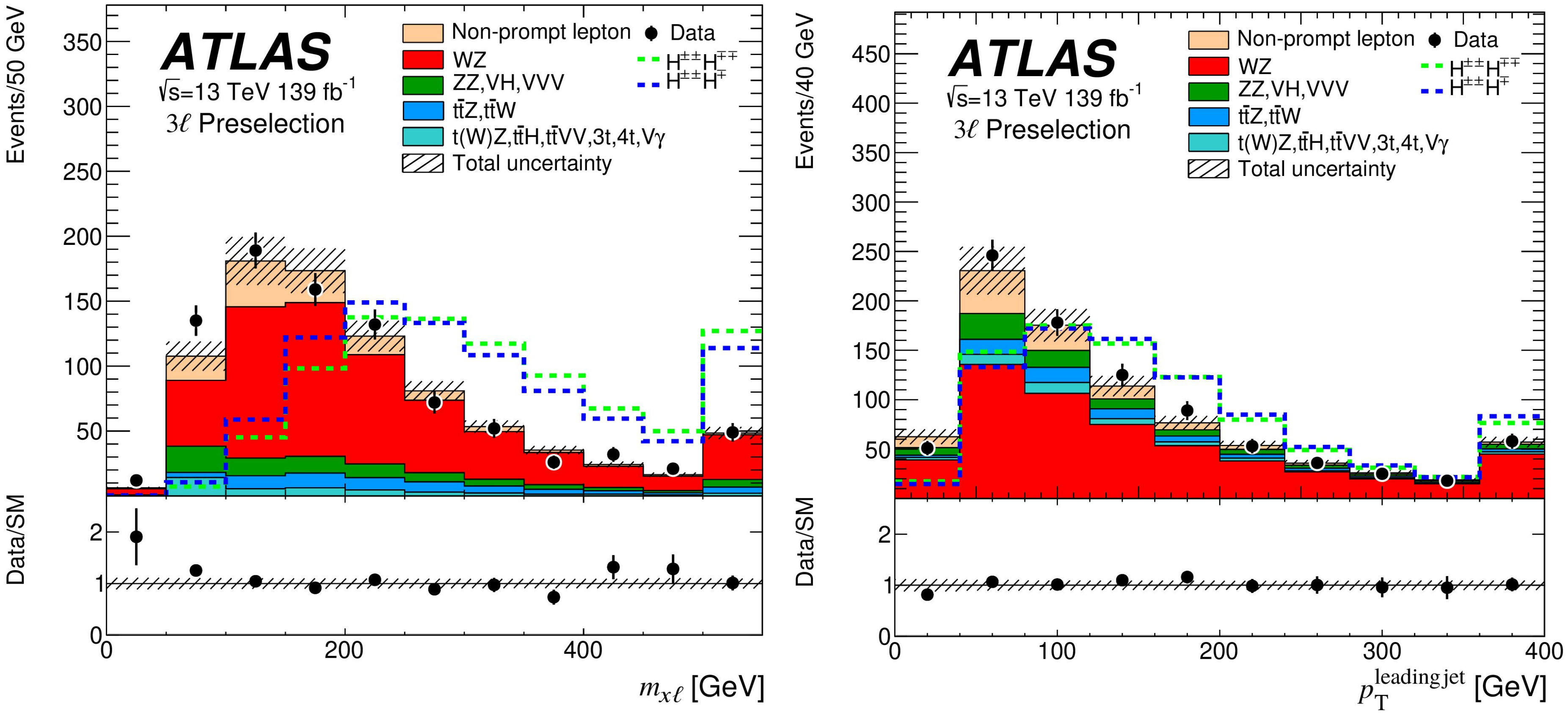
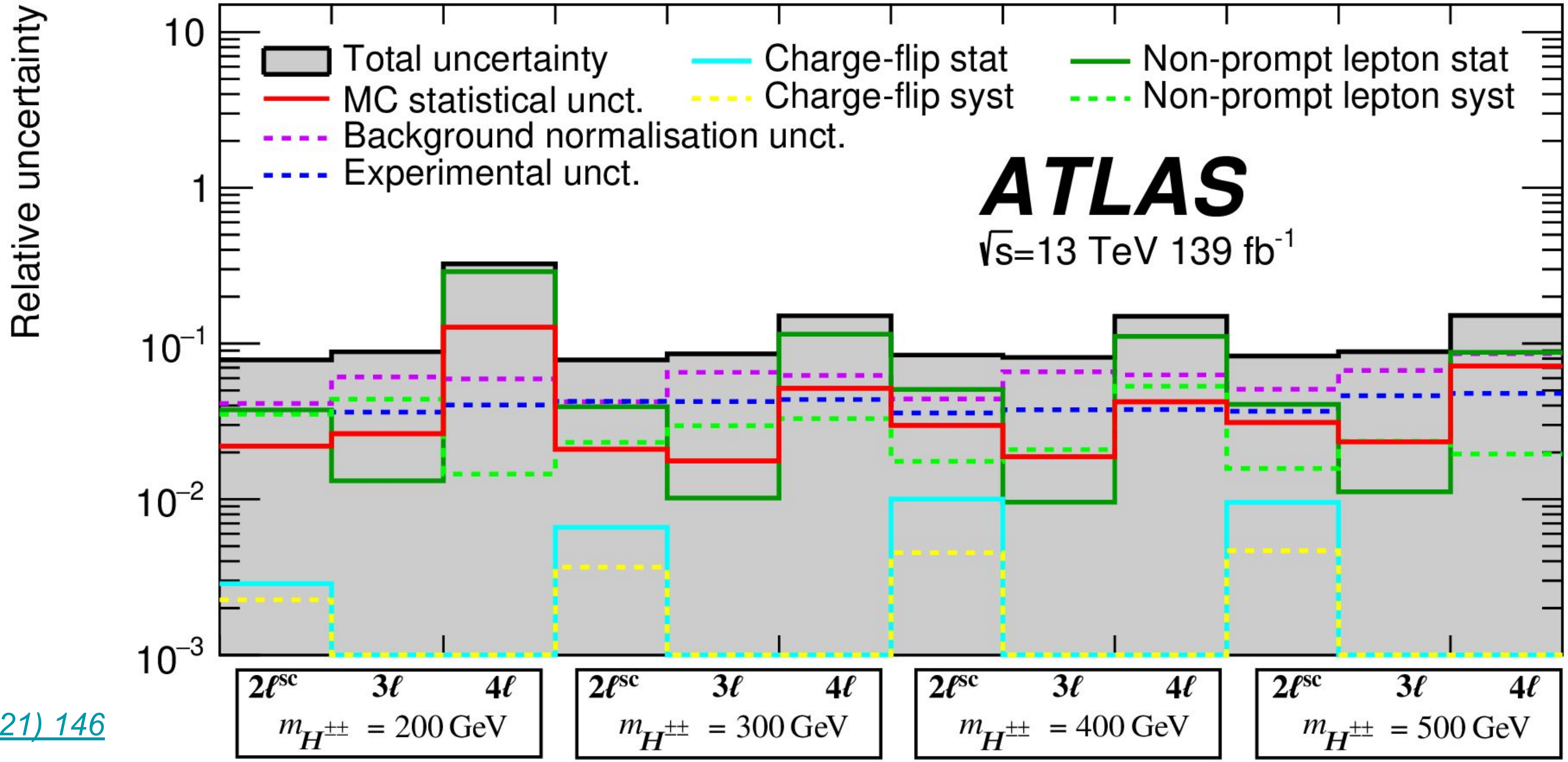
Search for doubly and singly charged Higgs bosons:



Search for doubly and singly charged Higgs bosons:

Contributions from different categories of uncertainties relative to the expected background yields in the various SRs. The uncertainties are shown for the combination of the individual channels of the $2\ell^{sc}$, 3ℓ and 4ℓ SRs.



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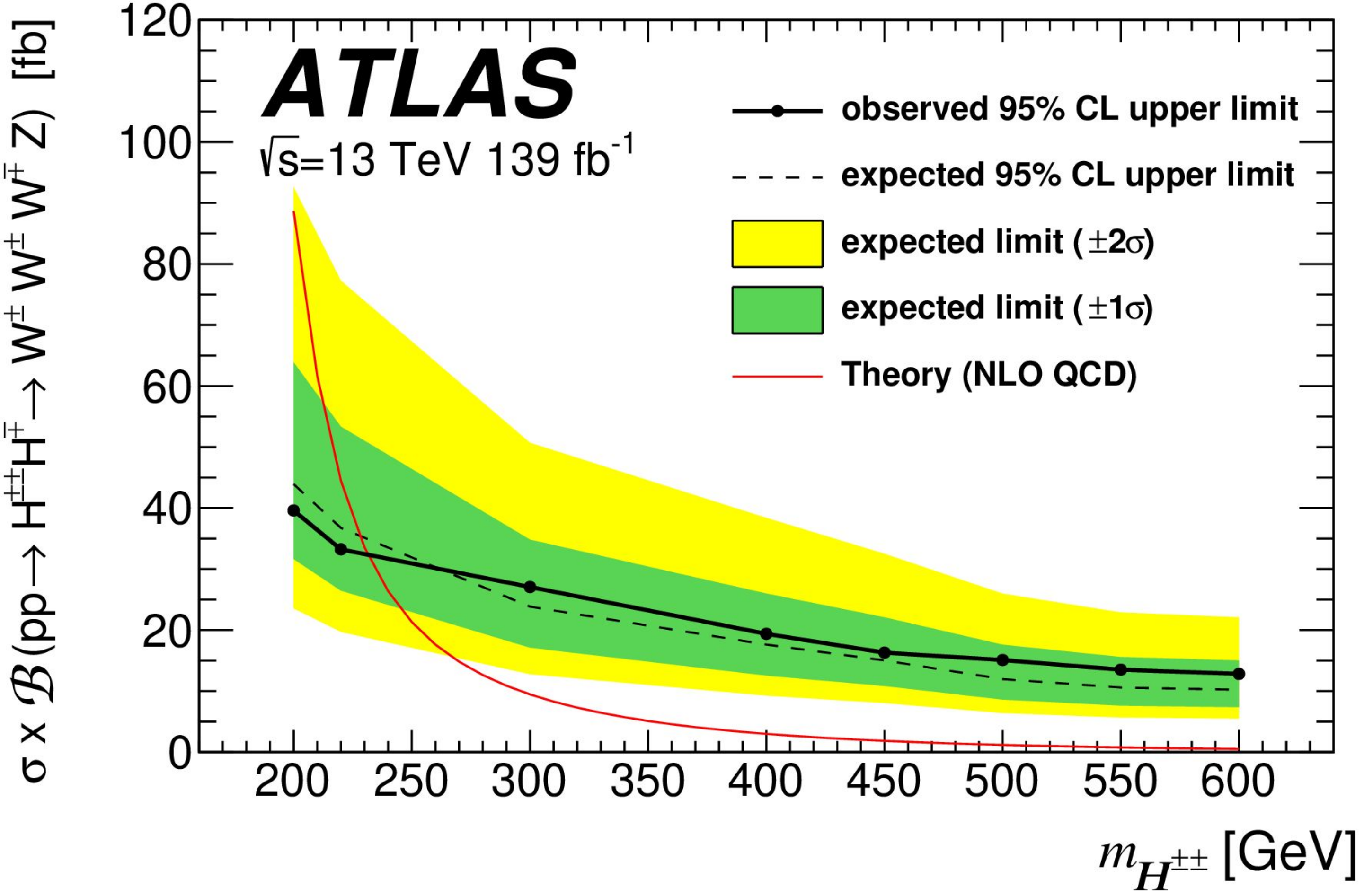
Search for doubly and singly charged Higgs bosons:



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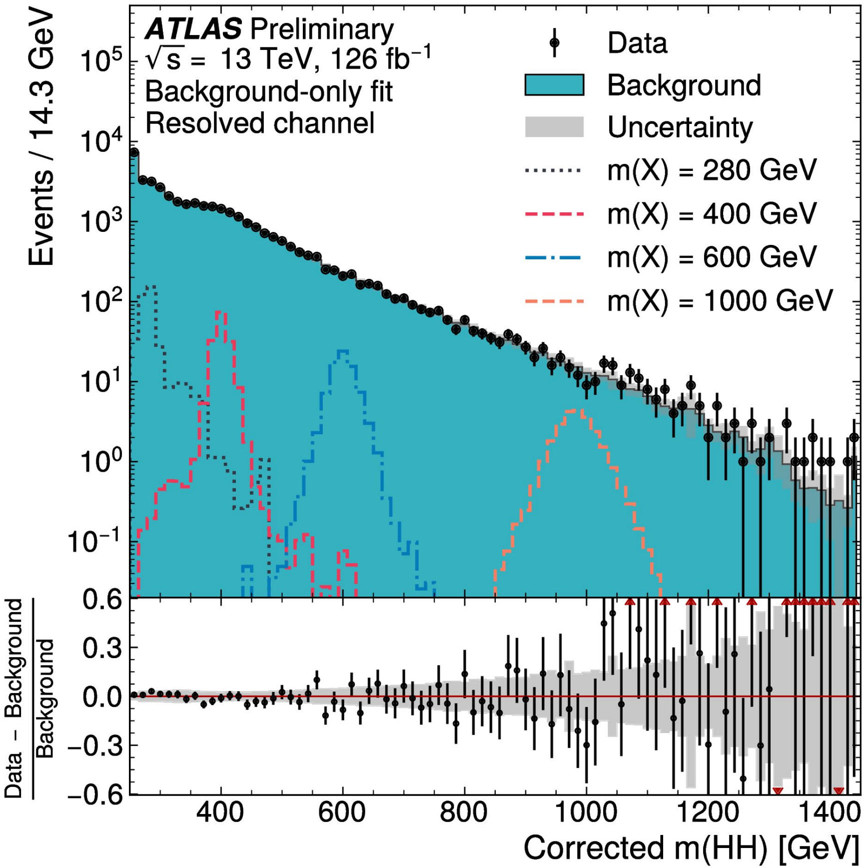
Search for resonances in X → aa→ bbbb decays:

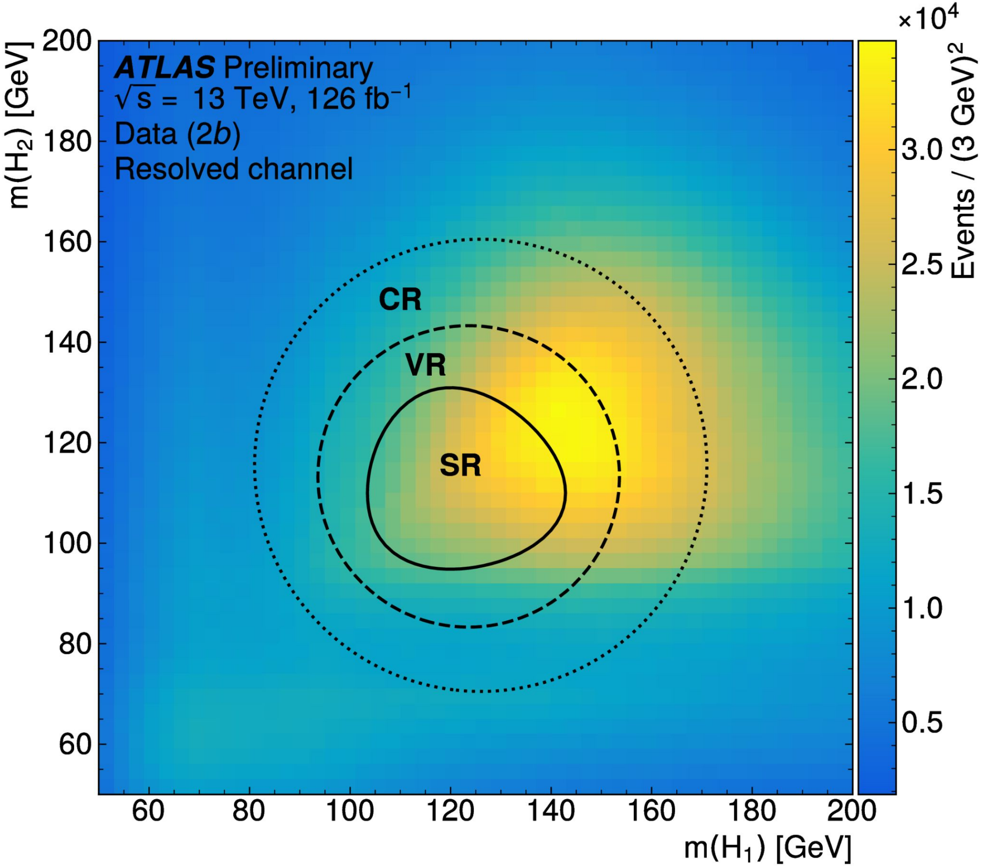
Search and control regions used in the analysis. A selection on the subleading jet double-b -tagger discriminant D^{bb}> 0.6 further separates each region into the passing and failing categories.

	m_{asym}	$\Delta\eta$	D_{j1}^{bb}
tight search region	< 0.1	< 1.5	> 0.8
loose search region	$\in [0.1, 0.25]$	< 1.5	> 0.8
tight $\Delta\eta$ sideband	< 0.1	> 1.5	> 0.8
loose $\Delta\eta$ sideband	$\in [0.1, 0.25]$	> 1.5	> 0.8
tight double-b sideband	< 0.1	< 1.5	$[-0.8, 0.3]$
loose double-b sideband	$\in [0.1, 0.25]$	< 1.5	$[-0.8, 0.3]$

CMS-PAS-B2G-20-003

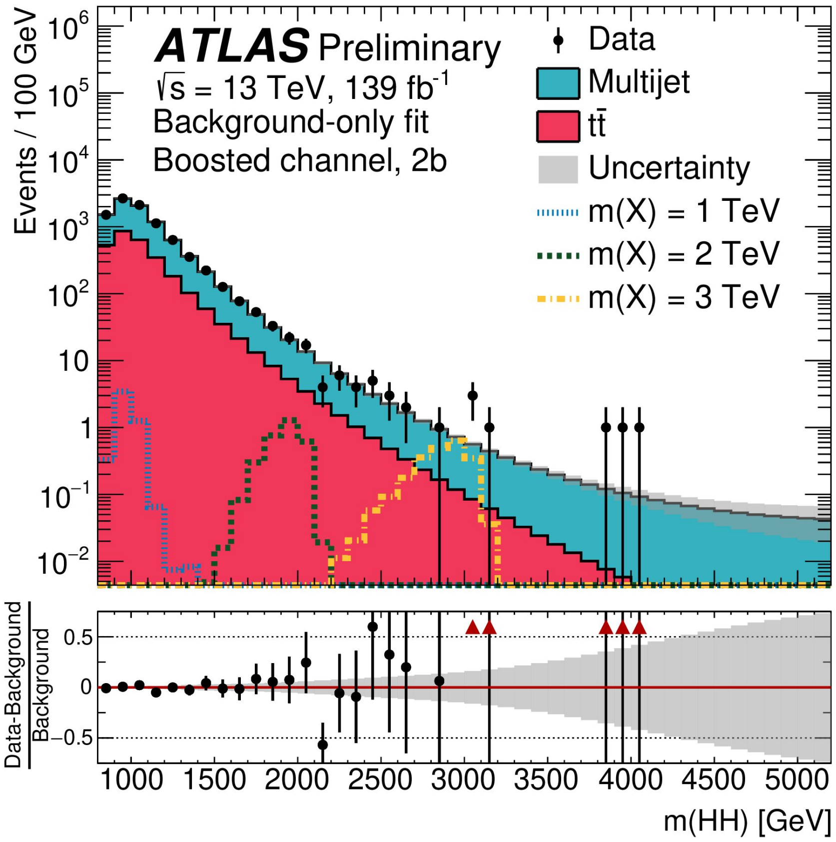
Search for resonances in X → hh→ bbbb decays:

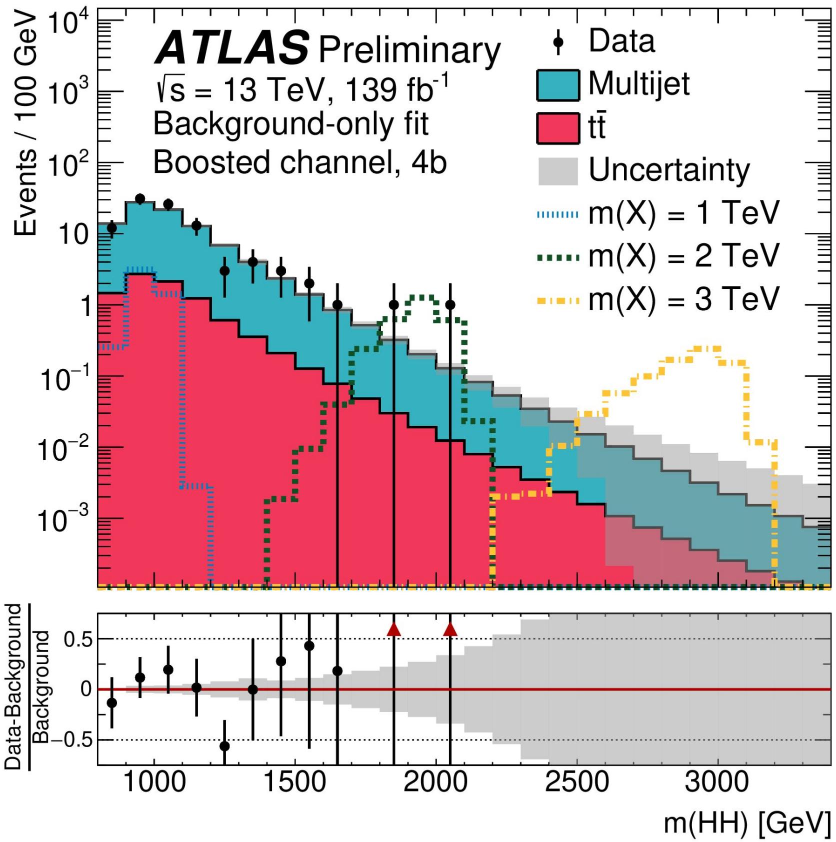




ATLAS-CONF-2021-035

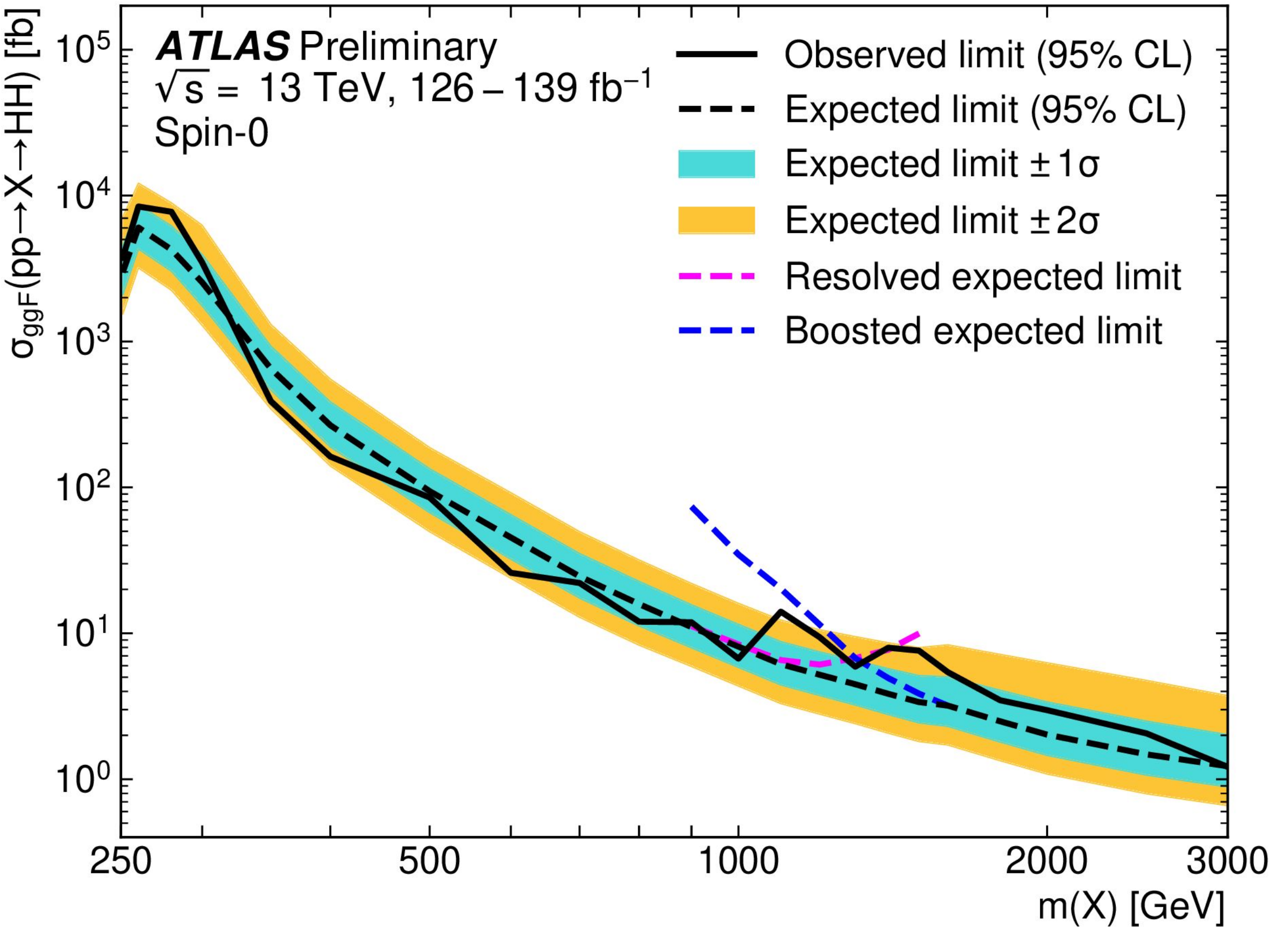
Search for resonances in X → hh→ bbbb decays:





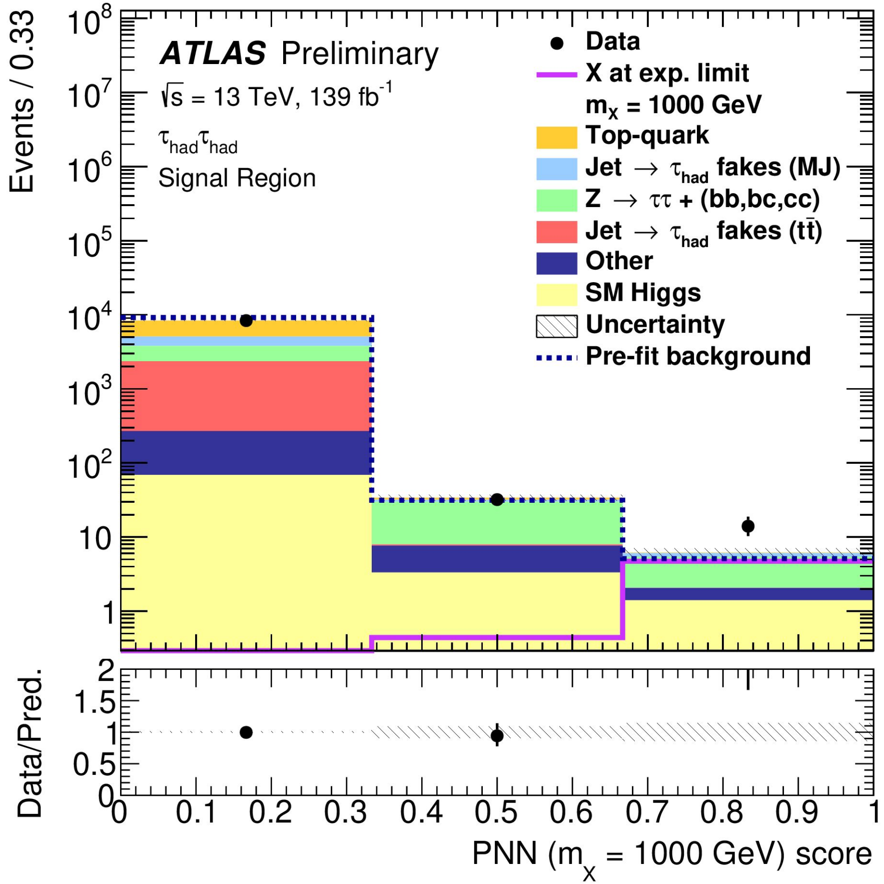
ATLAS-CONF-2021-035

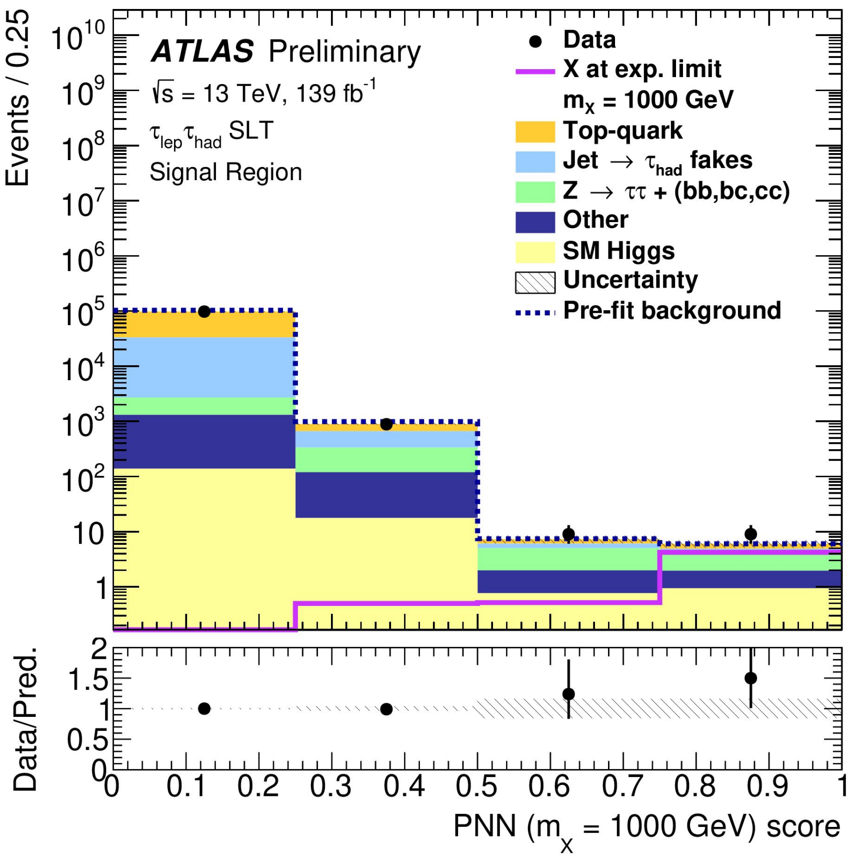
Search for resonances in X → hh→ bbbb decays:



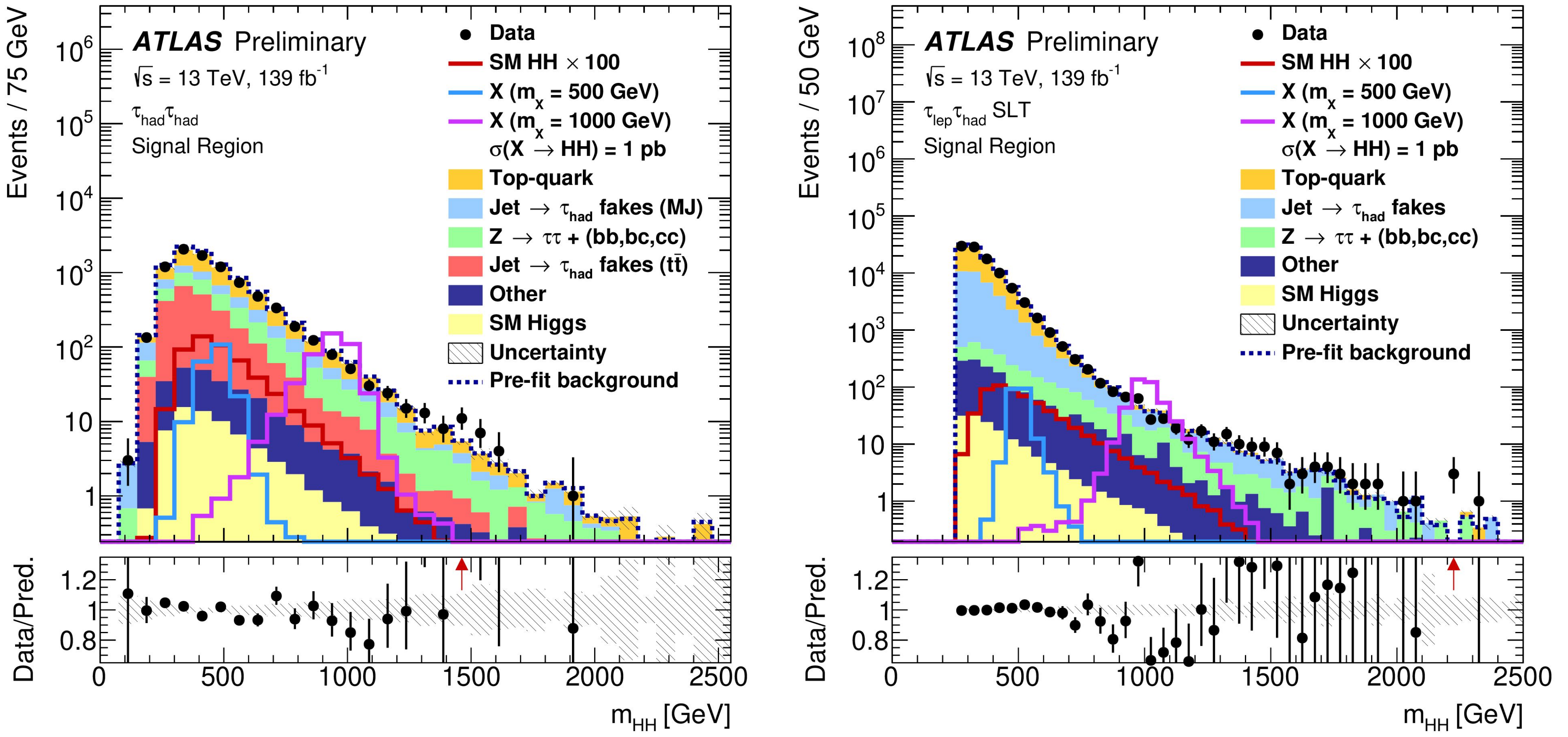
ATLAS-CONF-2021-035

Search for resonances in X → hh→ bbττ decays:





Search for resonances in X → hh→ bbττ decays:



Search for resonances in X → hh→ bbττ decays:

Variables used as inputs to the MVAs in the three analysis categories. The same choice of input variables is used for the resonant and non-resonant production modes

ATLAS-CONF-2021-030

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		✓	
$\Delta\phi(\tau\tau, bb)$		✓	
$\Delta\phi(\ell, \mathbf{p}_{\text{T}}^{\text{miss}})$			✓
$\Delta\phi(\ell\tau, \mathbf{p}_{\text{T}}^{\text{miss}})$			✓
S_{T}			✓

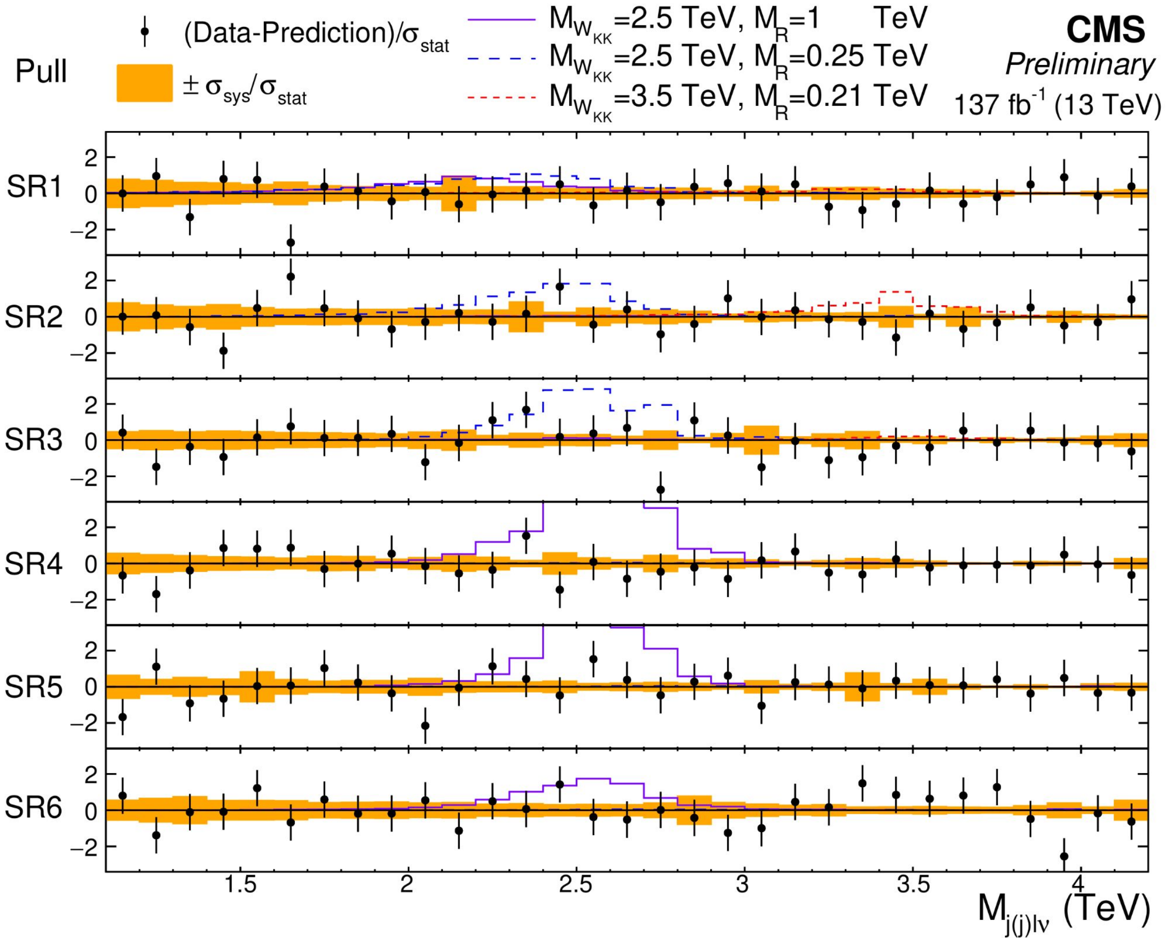
Search for resonances in X → hh→ bbττ decays:

Breakdown of the relative contributions to the uncertainty in the extracted signal cross-sections, as determined in the likelihood fit to data. These are obtained by fixing the relevant nuisance parameters in the likelihood fit, and subtracting the obtained uncertainty on the fitted signal cross-sections in quadrature from the total uncertainty, and then dividing the result by the total uncertainty.

ATLAS-CONF-2021-030

Uncertainty source	Non-resonant HH	Resonant $X \to HH$		
		300 GeV	500 GeV	1000 GeV
Data statistical	81%	75%	89%	88%
Systematic	59%	66%	46%	48%
$t\bar{t}$ and Z + HF normalisations	4%	15%	3%	3%
MC statistical	28%	44%	33%	18%
Experimental				
Jet and $E_{\mathrm{T}}^{\mathrm{miss}}$	7%	28%	5%	3%
b-jet tagging	3%	6%	3%	3%
$\tau_{\text{had-vis}}$	5%	13%	3%	7%
Electrons and muons	2%	3%	2%	1%
Luminosity and pileup	3%	2%	2%	5%
Theoretical and modelling				
Fake-$\tau_{\text{had-vis}}$	9%	22%	8%	7%
Top-quark	24%	17%	15%	8%
$Z(\to \tau\tau)$ + HF	9%	17%	9%	15%
Single Higgs boson	29%	2%	15%	14%
Other backgrounds	3%	2%	5%	3%
Signal	5%	15%	13%	34%

Search for resonances decaying to triple W-boson final states:



CMS-PAS-B2G-20-001