Searches for Non-SM Higgs Bosons and for BSM Decays of the Higgs Boson at the ATLAS Experiment

QCD@LHC 2018

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Introduction

- Discovery of a neutral scalar particle of mass ~ 125 GeV at the LHC confirmed the predicted electroweak symmetry breaking mechanism of the SM
- Experimental results show consistency with the SM Higgs boson
- Is there only one Higgs doublet (SM) or the Higgs sector is more complex?
- Various BSM models predict additional Higgs bosons:
  - Additional EW singlet: h, H
  - Two Higgs Doublet Model (2HDM): $h, H, A, H^{\pm}$
  - Two Higgs doublet + singlet Model
  - Higgs triplet models (SM doublet + triplet): $H^{\pm\pm}$

Strategies which use Higgs to find new physics:

Indirectly, by looking for non-standard properties of light Higgs (couplings, CP, LFV decays...)

Directly, by explicit search for BSM Higgs decaying to SM objects

Higgs decays to BSM states (light scalar resonances, invisible decays, LLP...)

Heavy Neutral Higgs

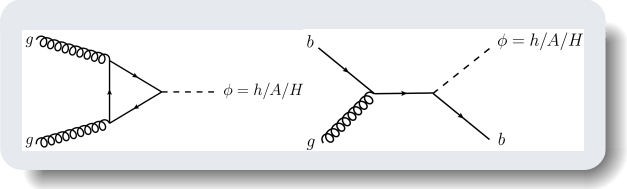
- Heavy neutral Higgs in fermion final states
  - In the MSSM, the heavy Higgs boson couplings to down-type fermions (τ, b) are strongly enhanced for a large part of the parameter space for large $\tan\beta$
- Heavy neutral Higgs in boson final states
  - In the EWS or 2HDM models heavy Higgs boson could decay into final states with Weak bosons

Searches for heavy neutral Higgs in ATLAS

$A/H \to \tau\tau$	JHEP 01 (2018) 055
$A \to Zh \to \ell\ell b\bar{b}$	JHEP 03 (2018) 174
$A \to ZH \to \ell\ell b\bar{b}$	Phys. Lett. B 783 (2018) 392
$H \to WW \to \ell\nu qq$	JHEP 03 (2018) 042
$H \to ZZ \to \ell\ell\ell\ell/\ell\ell\nu\nu$	Eur. Phys. J. C 78 (2018) 293
$X \to Z\gamma$	JHEP 10 (2017) 112
$X \to \gamma\gamma$	Phys. Lett. B 775 (2017) 105

Heavy Neutral Higgs

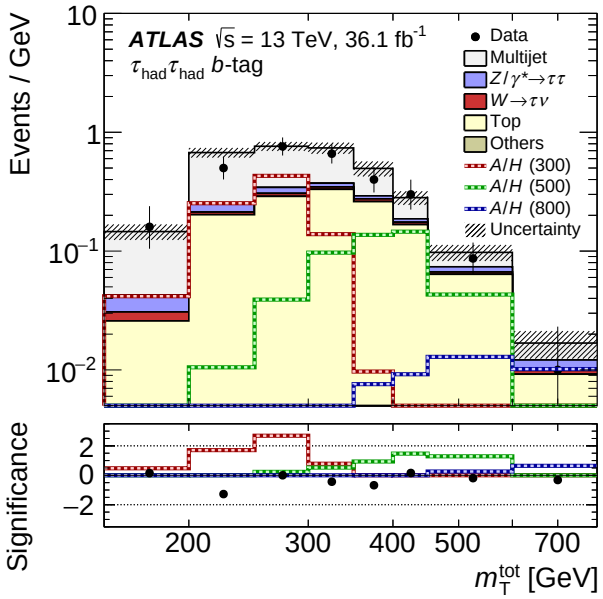
$A/H \to \tau\tau$ in 36.1 fb^{-1} of pp collisions at 13 TeV

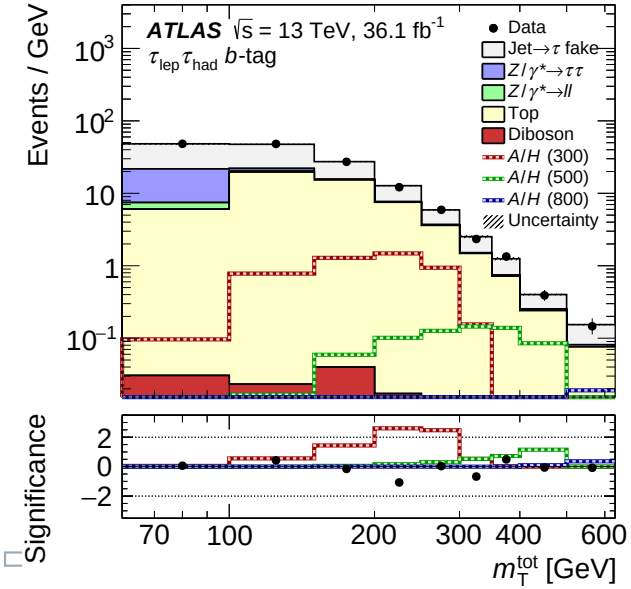


- Two τ decay modes considered:
  - All hadronic final state ($\tau_{\rm had}\tau_{\rm had}$), 0 or ≥ 1 b-jet
  - Semileptonic final state ($\tau_{\rm lep}\tau_{\rm had}$), 0 or ≥ 1 b-jet
- Both channels have good sensitivity
- Discriminating variable:

$$m_{\rm T}^{\rm tot} = \sqrt{(p_{\rm T}^{\tau_1} + p_{\rm T}^{\tau_2} + E_{\rm T}^{\rm miss})^2 - (\mathbf{p}_{\rm T}^{\tau_1} + \mathbf{p}_{\rm T}^{\tau_2} + \mathbf{E}_{\rm T}^{\rm miss})^2}$$

- Main backgrounds:
  - Misidentified jet as τ

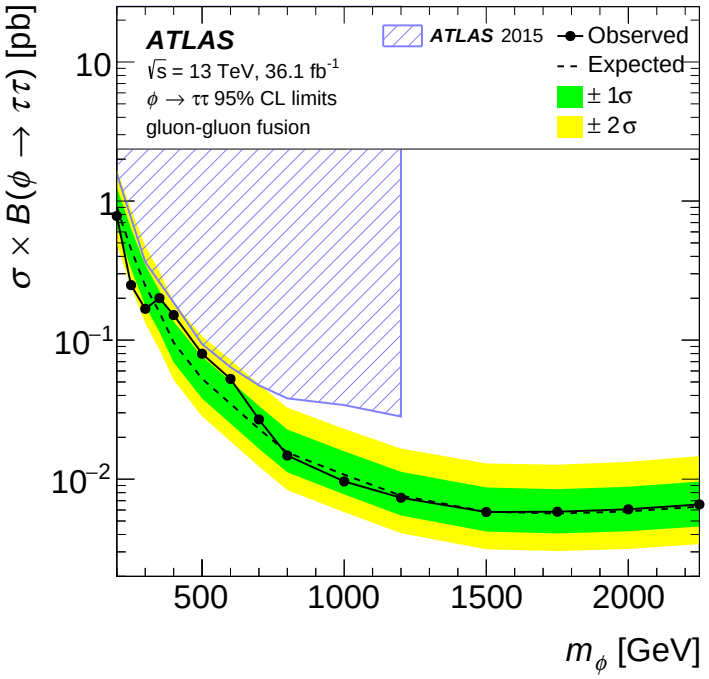


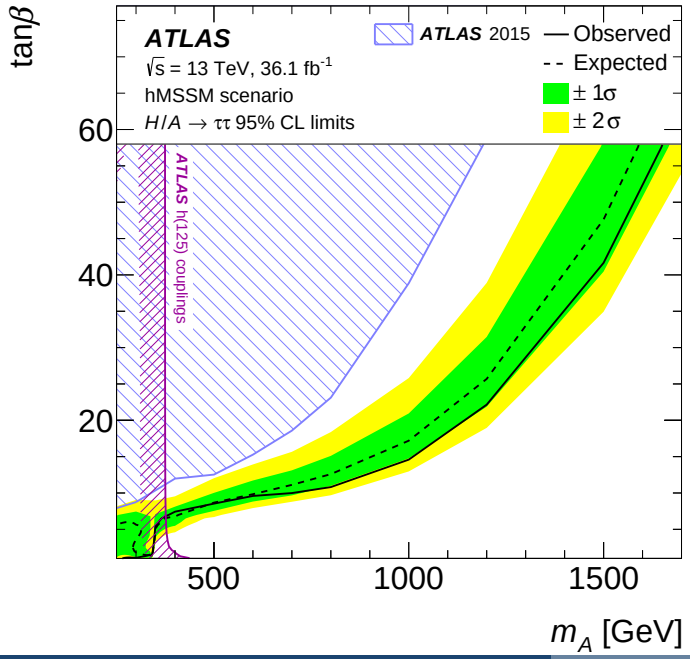


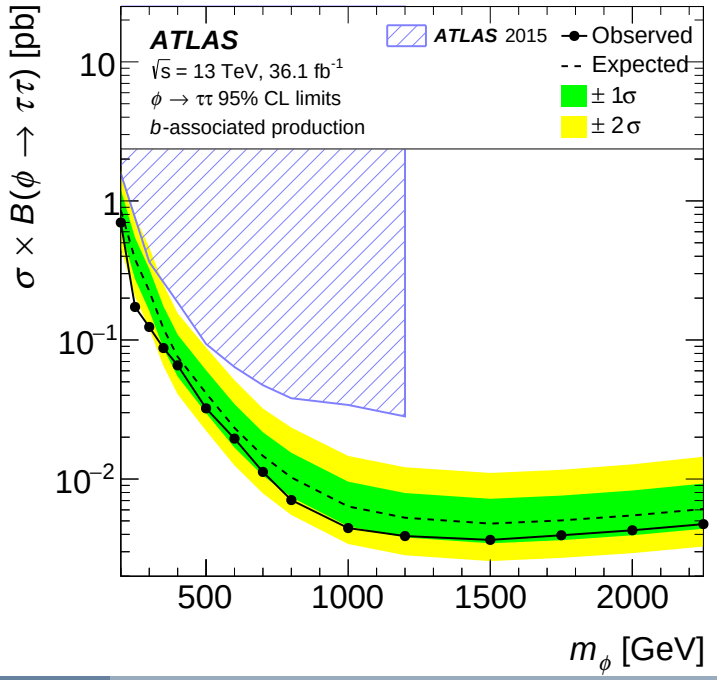
Heavy Neutral Higgs

$A/H \to \tau\tau$ in 36.1 fb^{-1} of pp collisions at 13 TeV

- Set limits as a function of $\phi = h/A/H$ mass for $\sigma(pp \to [bb]\phi) \times \mathrm{BR}(\phi \to \tau\tau)$:
  - ggF: 0.78 pb – 5.8 fb for m_ϕ range of 200 GeV – 2.25 TeV
  - b-associated: 0.7 pb – 3.7 fb for m_ϕ range of 200 GeV – 2.25 TeV
- Interpreted obtained results in context of hMSSM: $\tan\beta > 42$ for $m_\phi = 1.5$ TeV

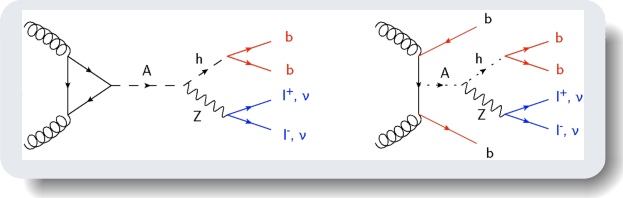




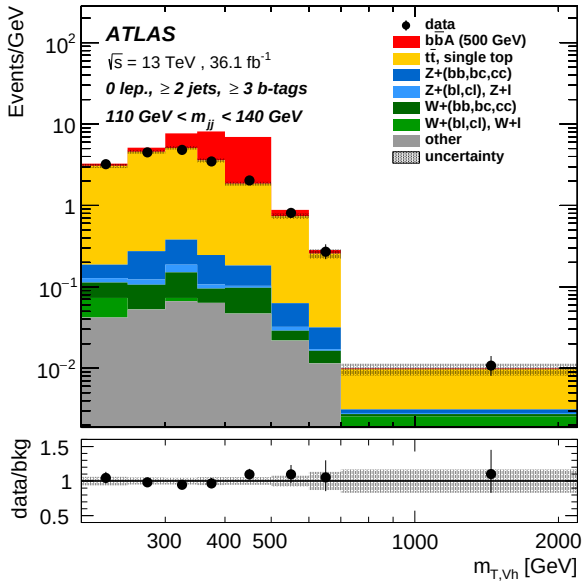


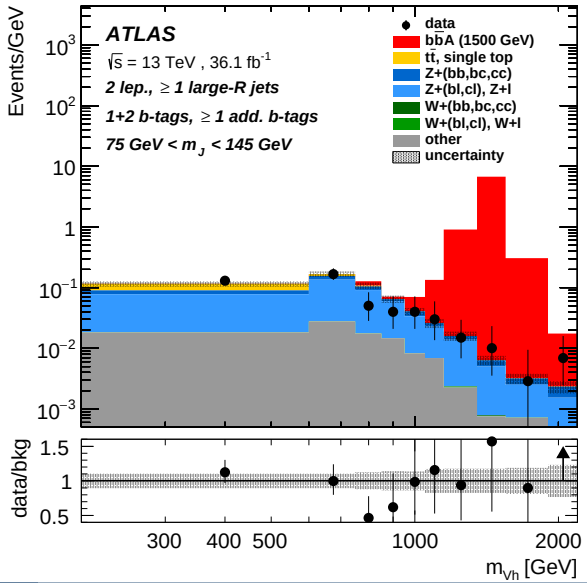
Heavy Neutral Higgs

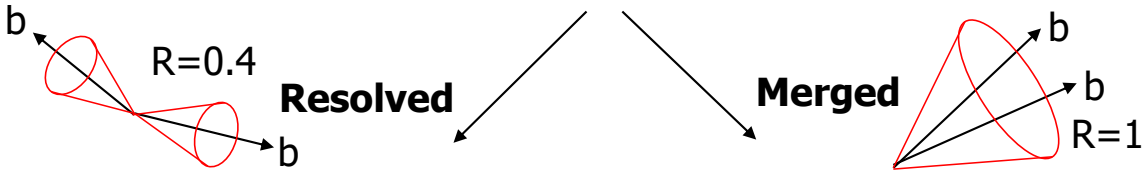
$A \to Zh \to \ell\ell b\bar{b}$ in 36.1 fb^{-1} of pp collisions at 13 TeV



- ggF and b-quark associated productions considered
- Two channels based on Z decays
- Main backgrounds:
  - $t\bar{t}$ and single top events
  - Z/W+jets events
- Additional b-jets from the associated b-quarks in the production process
- As m_A gets larger, h is boosted (higher momentum), resolved and merged categories



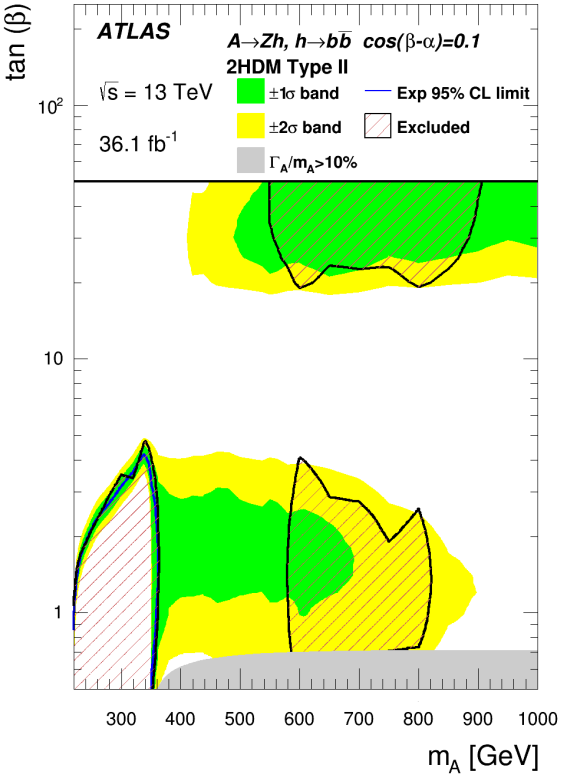


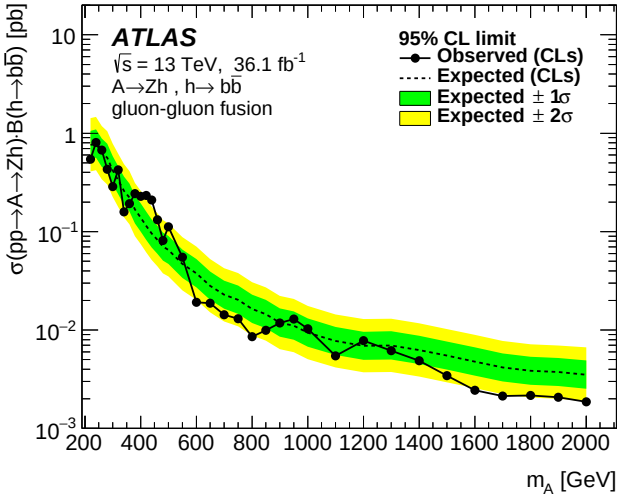


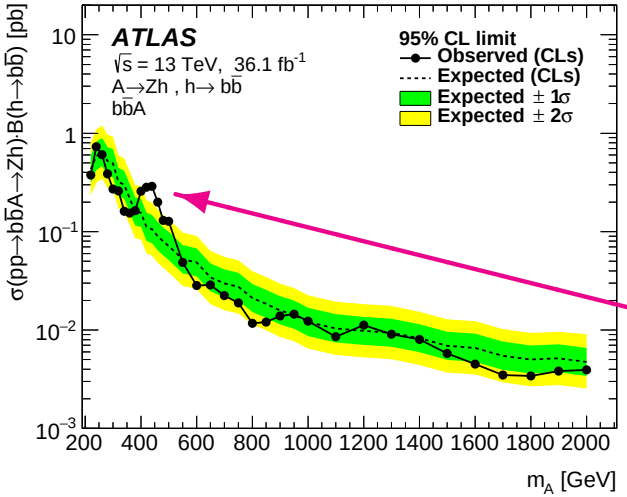
Heavy Neutral Higgs

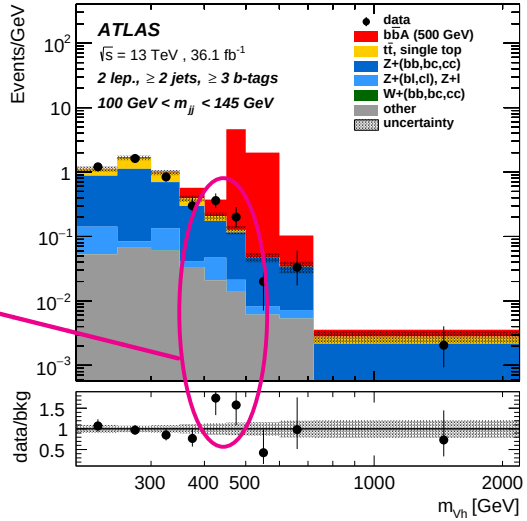
$A \to Zh \to \ell\ell b\bar{b}$ in 36.1 fb^{-1} of pp collisions at 13 TeV

- No significant excess over SM predictions
- Set limits as a function of m_A for:
  - $\sigma(pp \to A \to Zh) \times \mathrm{BR}(h \to b\bar{b})$ for ggF
  - $\sigma(pp \to b\bar{b}A \to Zh) \times \mathrm{BR}(h \to b\bar{b})$ for $b\bar{b}A$: excess at 440 GeV, 3.6 σ local and 2.4 σ global significance, arises mostly from 2-lepton $\geq$3 b-tag channel
- Interpreted results in context of 2HDM Type II ($\cos(\beta - \alpha) = 0.1$)



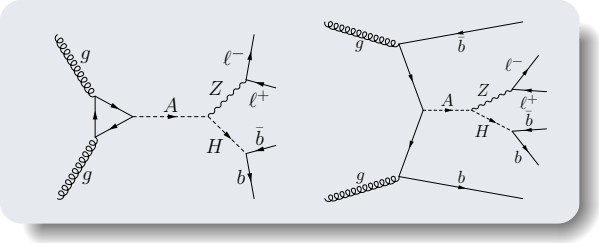




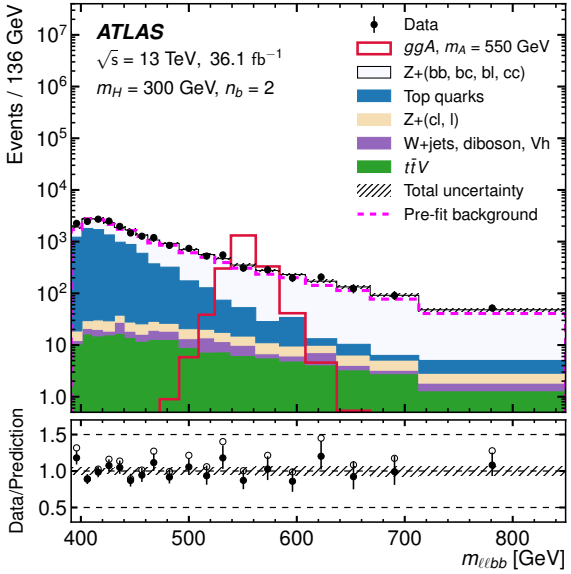


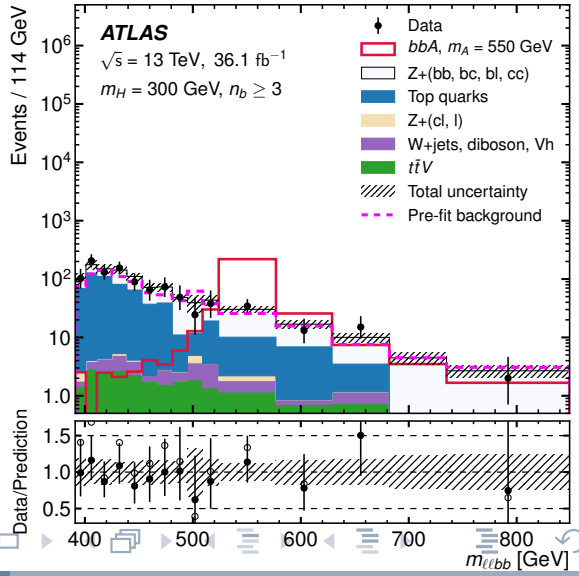
Heavy Neutral Higgs

$A \to ZH \to \ell\ell b\bar{b}$ in 36.1 fb^{-1} of pp collisions at 13 TeV



- Electroweak baryogenesis scenarios in 2HDM require that $m_A > m_H$
- Two channels for different production modes:
  - $= 2$ b-tag: ggF production
  - ≥ 3 b-tag: b-associated production
- The discriminant variable $m_{\ell\ell bb}$ from different m_{bb} windows scanned for excesses beyond the background expectations
  - steps of 10 GeV
  - $230 < m_A < 800$ and $130 < m_H < 700$ GeV
  - $m_A - m_H > 100$ GeV
- Main backgrounds:
  - $t\bar{t}$ and single top events
  - W/Z+jets events

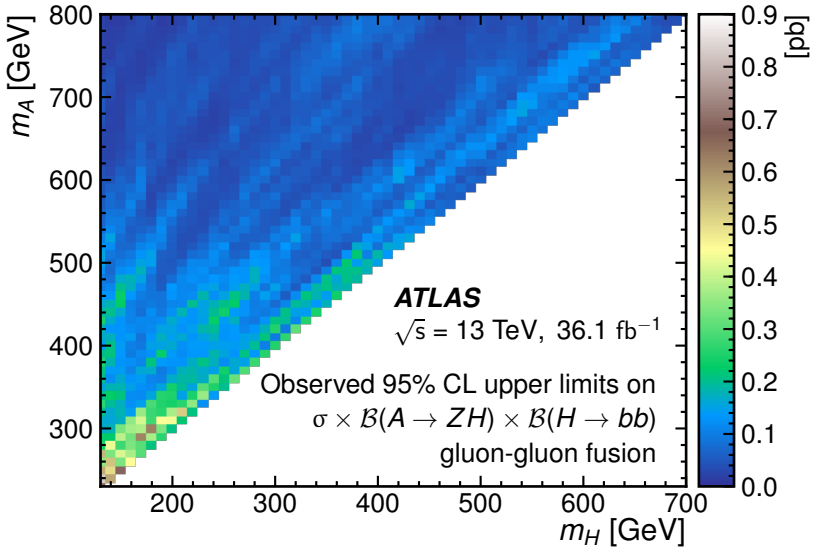


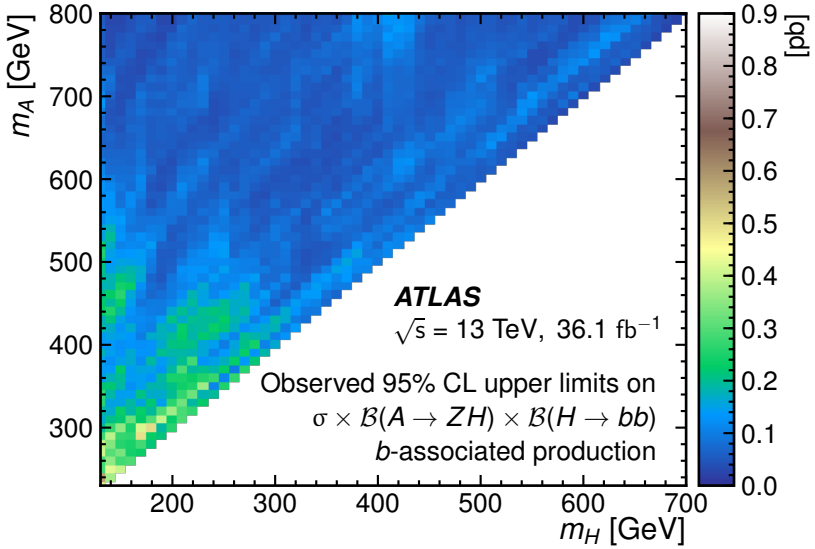


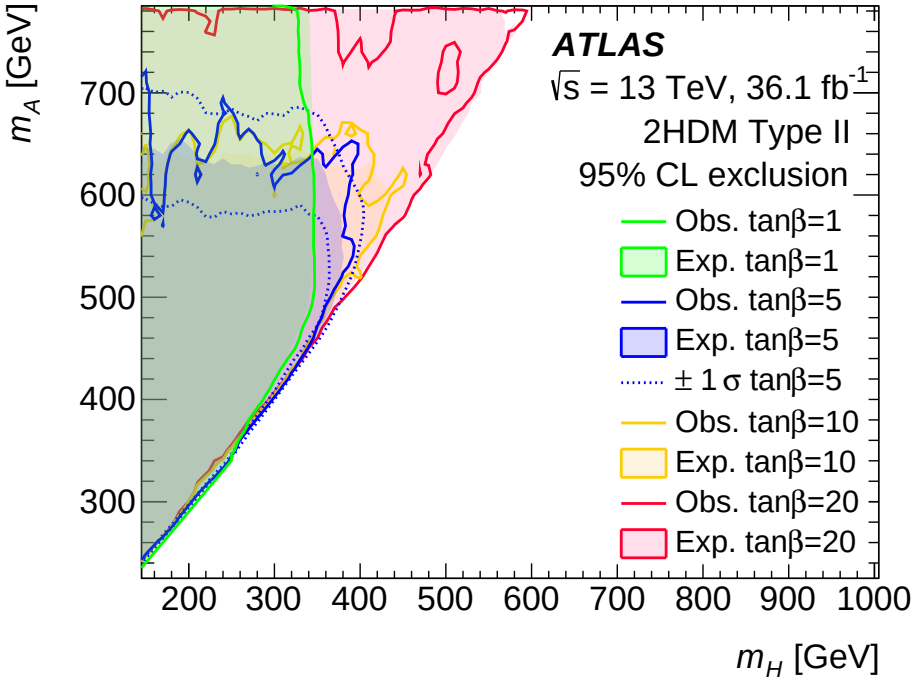
Heavy Neutral Higgs

$A \to ZH \to \ell\ell b\bar{b}$ in 36.1 fb^{-1} of pp collisions at 13 TeV

- Set limits as a function of H mass for $\sigma(pp \to A) \times \mathrm{B}(A \to ZH) \times \mathrm{B}(H \to bb)$
  - for ggF production: 14 – 830 fb
  - for b-associated production: 26 – 570 fb
- Interpreted results in context of 2HDM Type II: $m_H \leq 600$ GeV excluded at high $\tan\beta$

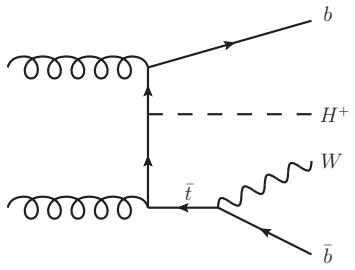


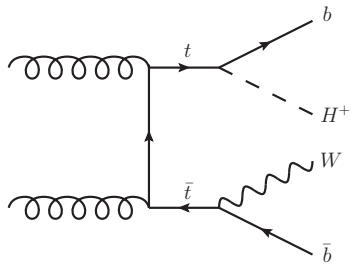


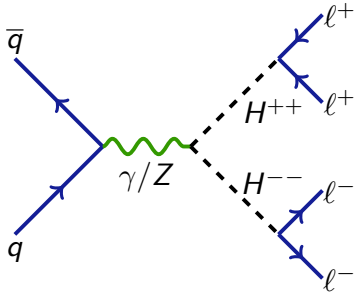


Charged Higgs

- Any extension to the Higgs sector, beyond adding a singlet scalar, implies existence of charged scalars (2HDM, NMSSM, Triplet...)
- Dominant production in association with top quarks in benchmark models
- At high mass $H^{\pm} \to tb$ is the dominant decay mode in type-II 2HDM
- $H^{\pm} \to \tau\nu$ remains significant for a large range of masses for high $\tan\beta$ in type-II 2HDM
- Addition of a Higgs triplet to SM gives doubly charged Higgs bosons $H^{\pm\pm}$





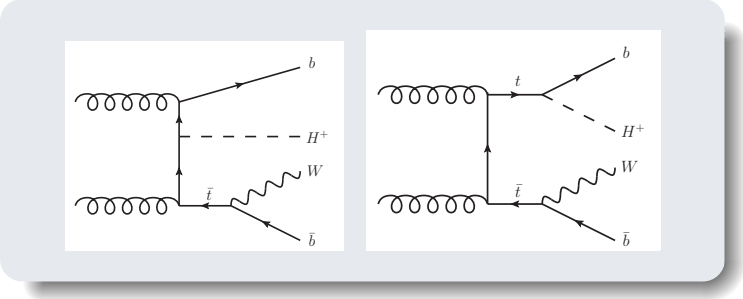


Charged Higgs searches in ATLAS

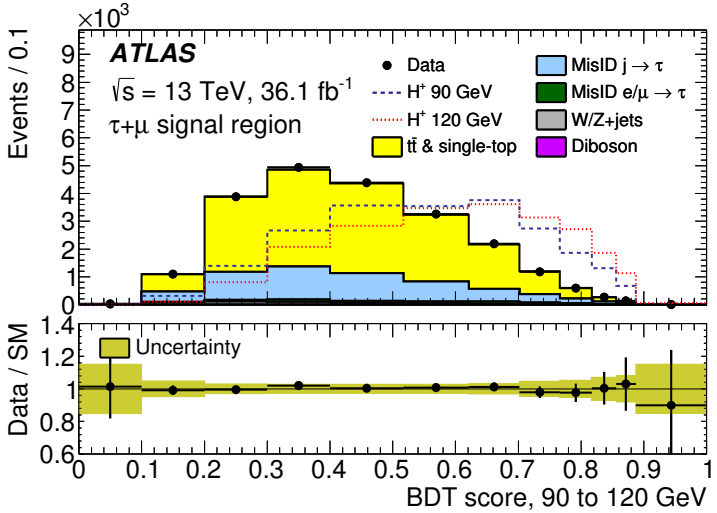
$H^{\pm} \to \tau\nu$	arXiv:1807.07915
$H^{\pm} \to tb$	arXiv:1808.03599
$H^{++}H^{--} \to W^+W^+W^-W^-$	arXiv:1808.01899
$H^{++}H^{--} \to \ell^+\ell^+\ell^-\ell^-$	Eur. Phys. J. C 78 (2018) 199

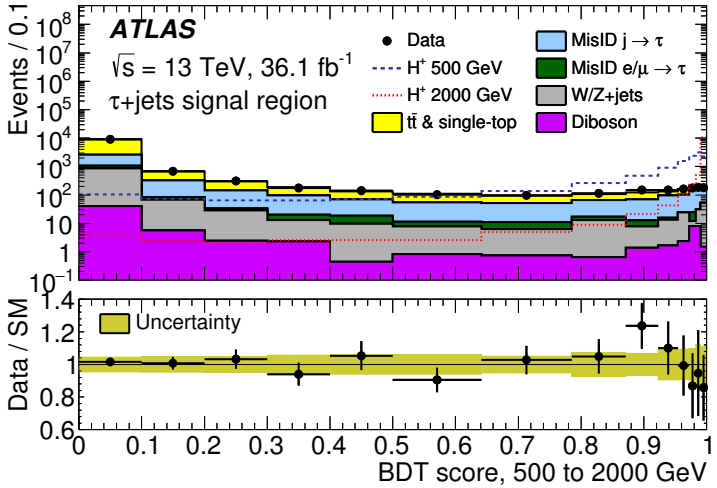
Charged Higgs

$H^{\pm} \to \tau\nu$ in 36.1 fb^{-1} of pp collisions at 13 TeV



- Search for $H^{\pm}$ over wide mass range
  - Low mass range (90-160 GeV)
  - Intermediate mass range ($m_{H^{\pm}} \approx m_t$) never probed experimentally
  - High mass range (200-2000 GeV)
- Two channels depending on associated t decay
  - 1 hadronic τ, veto events with ℓ, ≥ 3 jets (≥ 1 b-jet), $E_{\mathrm{T}}^{\mathrm{miss}}$
  - 1 hadronic τ, 1 ℓ, ≥ 1 jets (≥ 1 b-jet), $E_{\mathrm{T}}^{\mathrm{miss}}$
- Events classified with BDT from kinematic variables. BDT score used in statistical analysis
- Main backgrounds:
  - Misidentified jet as τ
  - $t\bar{t}$ and single top events



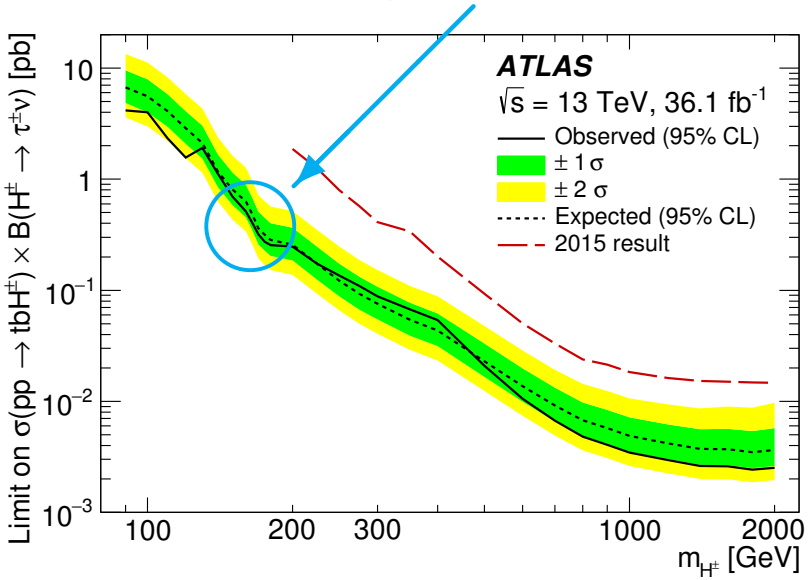


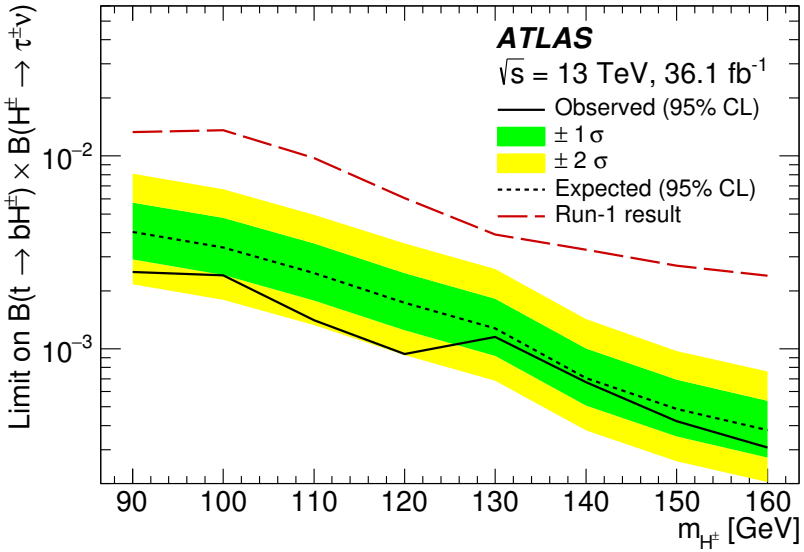
Charged Higgs

$H^{\pm} \to \tau\nu$ in 36.1 fb^{-1} of pp collisions at 13 TeV

- No significant excess over SM predictions observed
- Set limits as a function of $H^{\pm}$ mass for:
  - $\sigma(pp \to [b]tH^{\pm}) \times \mathrm{BR}(H^{\pm} \to \tau\nu)$ for full $H^{\pm}$ mass (bottom): 4.2 pb – 2.5 fb
  - $\mathrm{BR}(t \to bH^{\pm}) \times \mathrm{BR}(H^{\pm} \to \tau\nu)$ for low $H^{\pm}$ mass (top): 0.25% – 0.031%
- Compared the limits with
  - 2015 results for high $H^{\pm}$ mass
  - Run 1 results for low $H^{\pm}$ mass
- Significant gain with respect to previous results

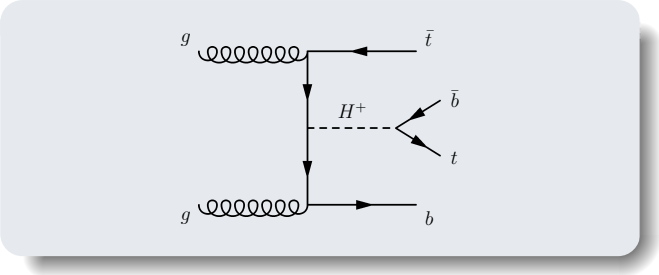
$H^{\pm}$ intermediate mass probed experimentally for a first time



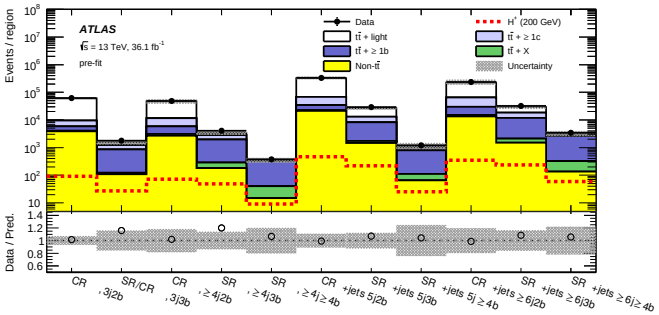


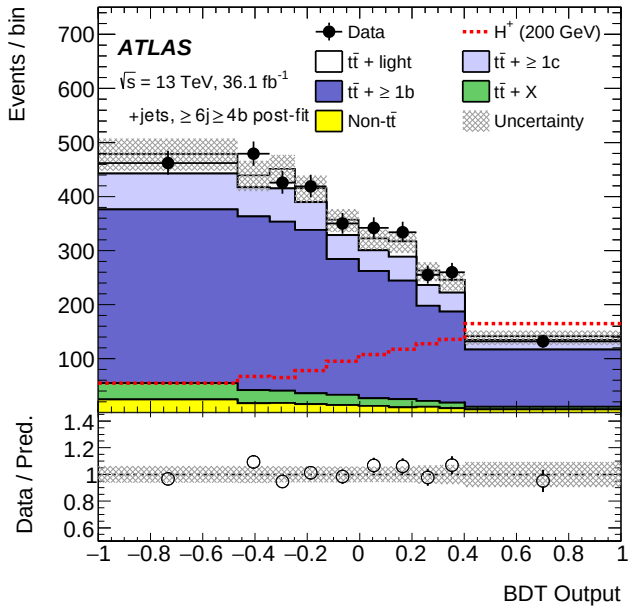
Charged Higgs

$H^{\pm} \to tb$ in 36.1 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV



- Search in the 200-2000 GeV mass range
- Multiple regions based on N(jets) and N(b-jets) to constrain the $t\bar{t}+\geq 1b$ and $t\bar{t}+\geq 1c$ backgrounds
- Events classified with BDT from kinematic variables
- Fit simultaneously in all regions
- Main backgrounds:
  - $t\bar{t}$+jets dominated by $t\bar{t}+\geq 1b$

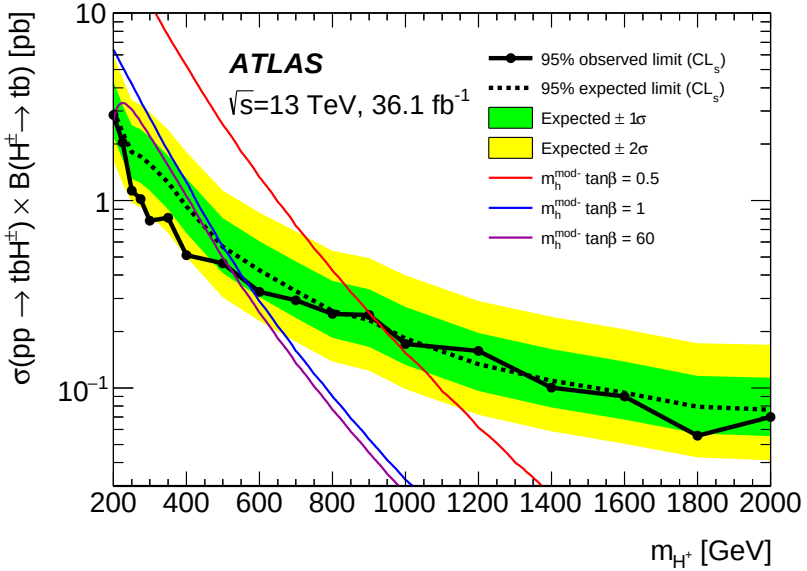


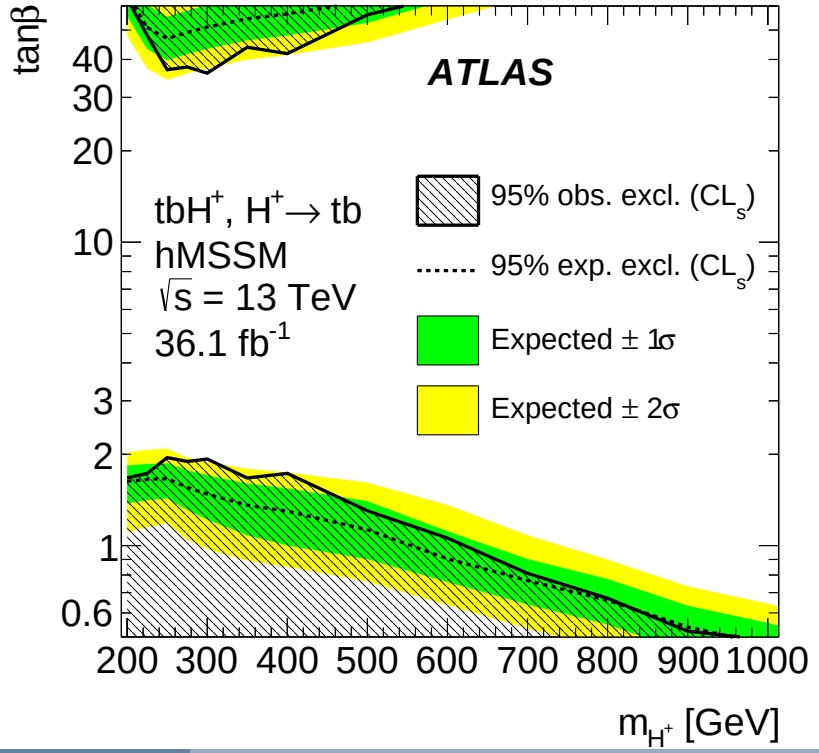


Charged Higgs

$H^{\pm} \to tb$ in 36.1 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV

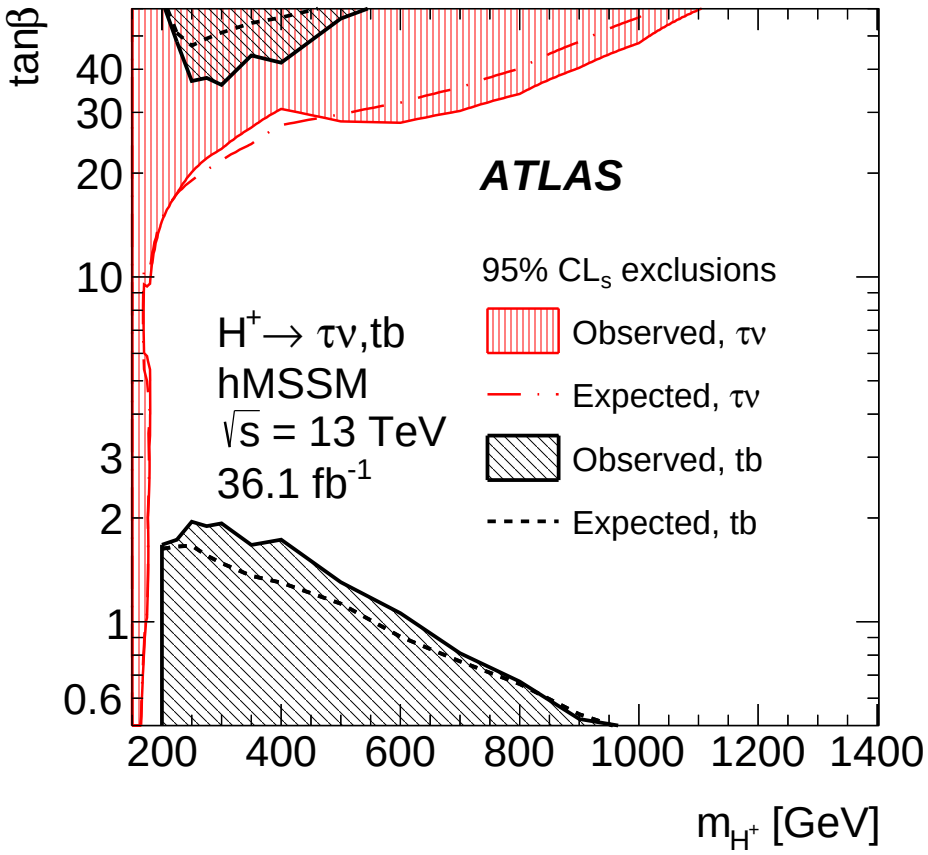
- No significant excess over SM predictions observed
- Set limits as a function of $H^{\pm}$ mass for $\sigma(pp \to tbH^{\pm}) \times \mathrm{BR}(H^{\pm} \to tb)$: 2.9 pb – 70 fb
- Interpreted obtained results in context of hMSSM and $m_h^{\text{mod-}}$ scenario:
  - $0.5 < \tan\beta < 1.95$ excluded for $m_{H^{\pm}} = 200$ GeV
  - $\tan\beta > 36$ excluded for $220 < m_{H^{\pm}} = 540$ GeV

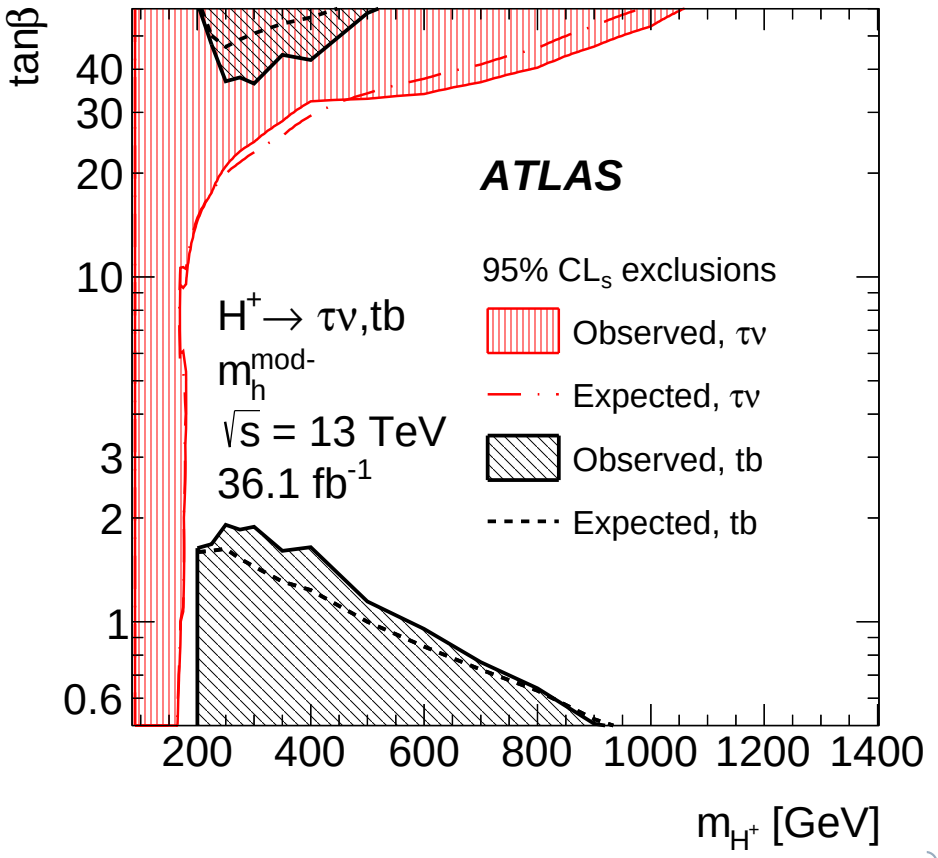




Common $H^{\pm} \to \tau\nu$ and $H^{\pm} \to tb$ Results

- Superposition of the $H^{\pm} \to \tau\nu$ and $H^{\pm} \to tb$ exclusion limits in context of hMSSM and $m_h^{\text{mod-}}$ scenario:
  - $m_{H^{\pm}} < 1100$ GeV excluded for $\tan\beta > 60$
  - All $\tan\beta$ values excluded for $m_{H^{\pm}} < 160$ GeV





Beyond Standard Model Decays of the Higgs Boson

- Exotic Higgs boson decays are a powerful probe for BSM physics
- Very narrow Higgs decay width provides the sensitivity to small couplings to non-SM particles
- Current measurements at the LHC constrain non-SM BR of the Higgs boson to less than 34% at 95% CL
- Exotic decays of the Higgs boson are predicted by NMSSM
- Searches for decay of the Higgs boson to a pair of spin-zero particles a or spin-1 Z_d decaying into a pair of SM particles

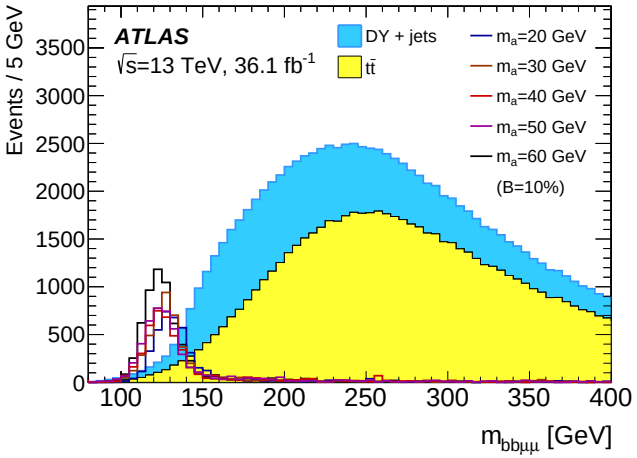
Searches for BSM decays of the Higgs boson in ATLAS

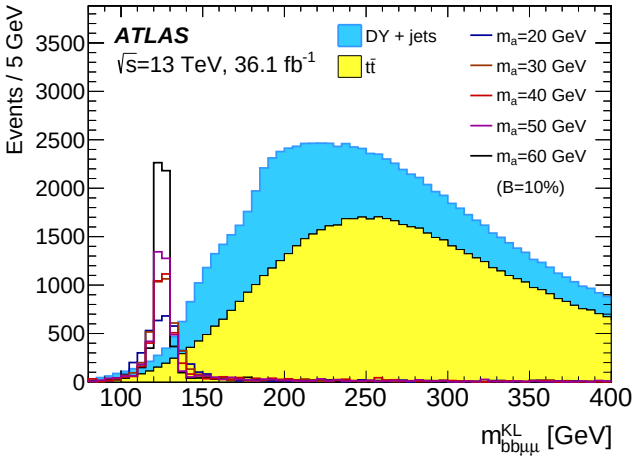
$h \to aa \to bb\mu\mu$	arXiv:1807.00539
$h \to aa \to \gamma\gamma jj$	Phys. Lett. B 782 (2018) 750
$h \to aa \to bbbb$	arXiv:1806.07355
$h \to aa/ZZ_d/Z_dZ_d \to \ell\ell\ell\ell$	JHEP 06 (2018) 166

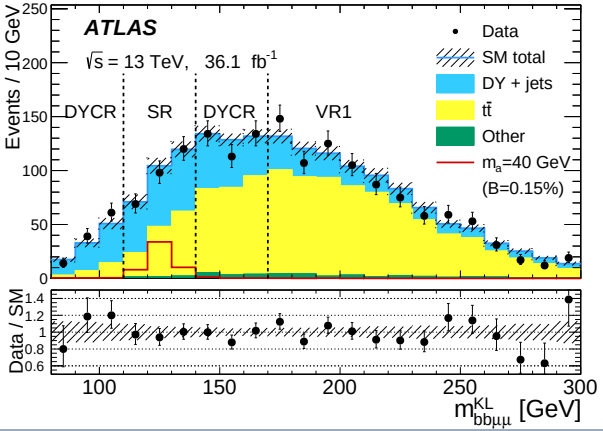
BSM decays of the Higgs Boson

$h \to aa \to bb\mu\mu$

- Signature: 2 μ, 2 jets, Higgs mass window, upper cut on $E_{\mathrm{T}}^{\mathrm{miss}}$
- $m_{\mu\mu}$ mass resolution is 10x better than m_{bb}
- Kinematic fit exploiting the symmetry of $h \to aa$ decays to test the compatibility of an event with the $m_{\mu\mu} \simeq m_{bb}$. Fit finds the energies of the b-jets that maximize the likelihood
- 2x improvement in $m_{\mu\mu bb}$ resolution
- Main backgrounds
  - Drell-Yan dimuon events
  - Top events



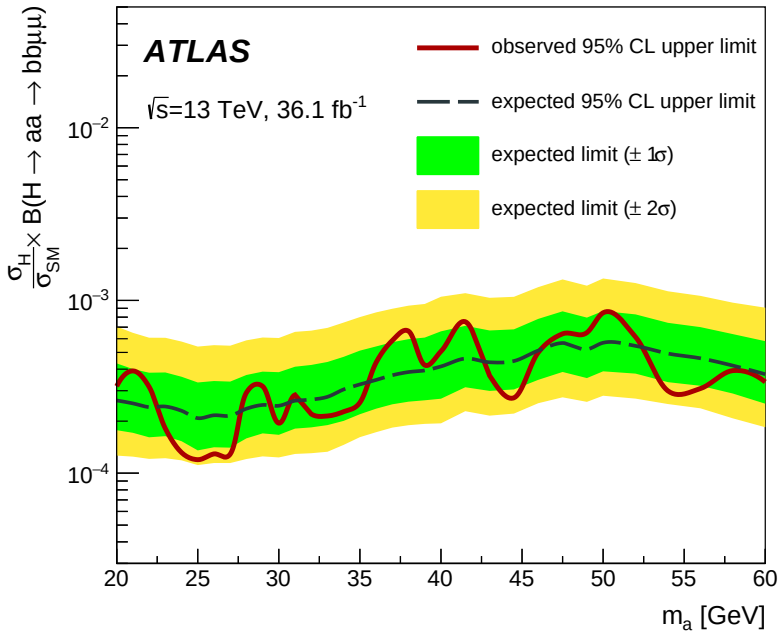


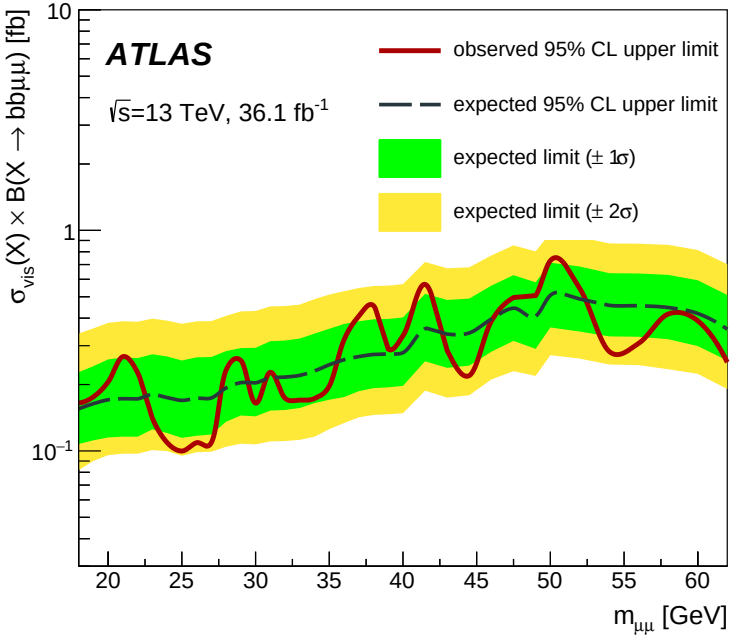


BSM decays of the Higgs Boson

$h \to aa \to bb\mu\mu$

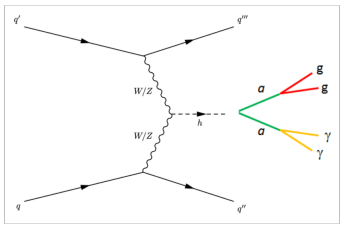
- No significant excess over SM predictions observed
- Limits set for:
  - $\mathrm{BR}(h \to aa \to bb\mu\mu)$ given the SM Higgs boson production cross section in the ggF, VBF and VH modes as a function of m_a: 10^{-4} – 10^{-3} for m_a range 20 – 60 GeV
  - visible cross section for new physics times branching ratio to the $bb\mu\mu$ final state: 0.1 – 0.73 fb for $m_{\mu\mu}$ between 18 and 62 GeV



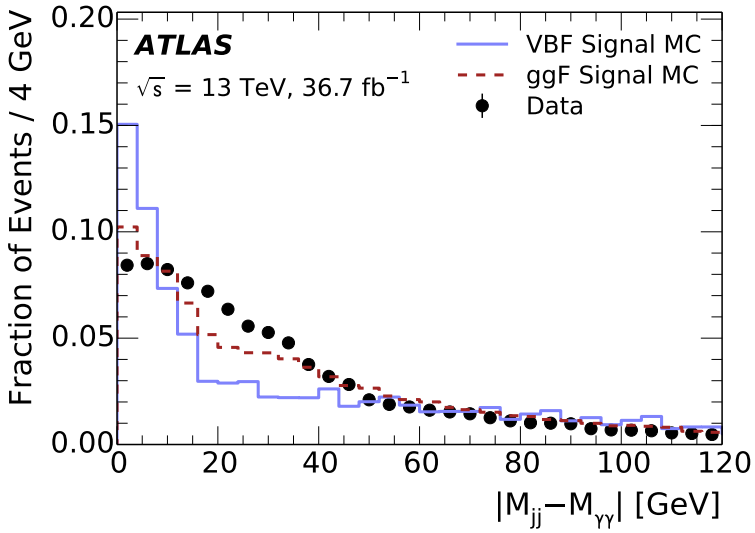


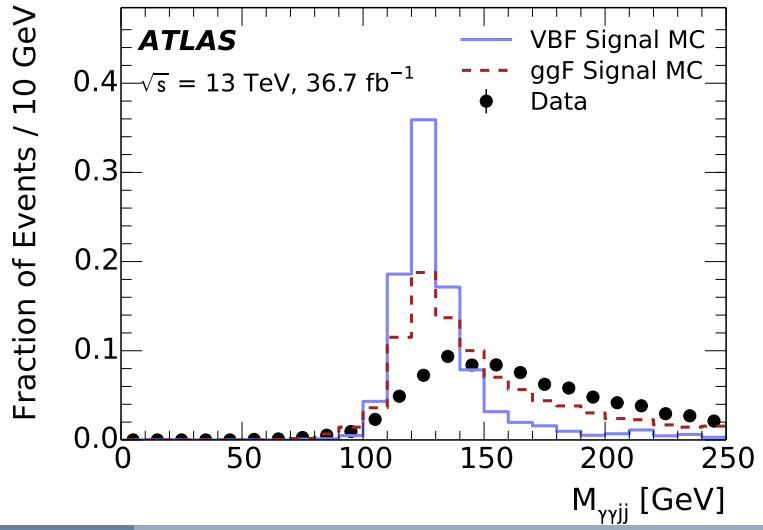
BSM decays of the Higgs Boson

$h \to aa \to \gamma\gamma jj$



- Final state relevant in models where the fermionic decays are suppressed. The a boson only decays to photons or gluons
- VBF production mode provides experimental handles to suppress backgrounds
- ≥ 4 jets, p_{T}^{j1}, m_{jj}^{VBF}, $m_{\gamma\gamma jj}$, $|m_{jj} - m_{\gamma\gamma}|$
- Main backgrounds:
  - $\gamma\gamma$+jets events estimated using data driven method

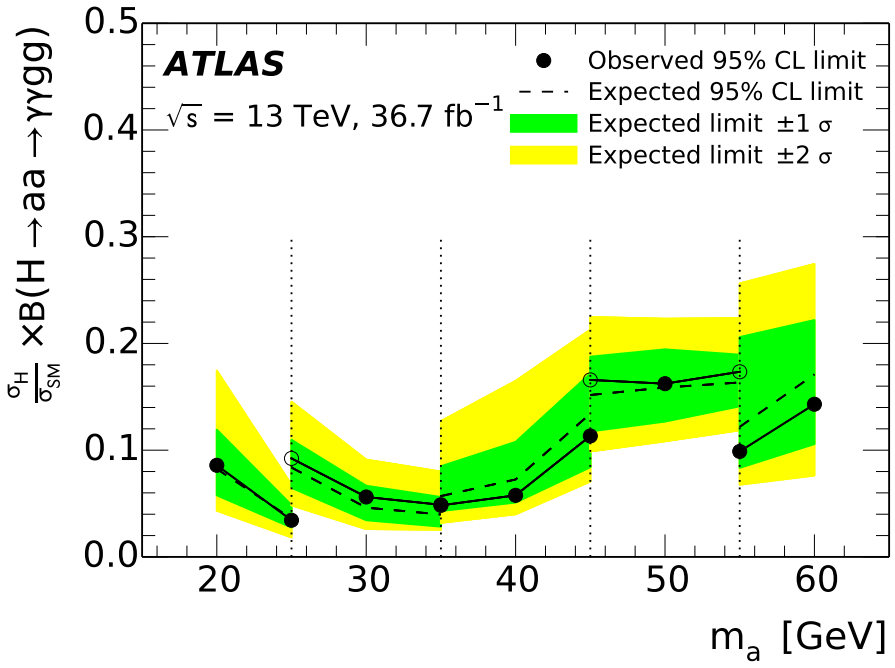




BSM decays of the Higgs Boson

$h \to aa \to \gamma\gamma jj$

- No significant excess over SM predictions observed
- Set limits as a function of m_a for $\sigma(pp \to H) \times \mathrm{BR}(H \to aa \to \gamma\gamma gg)$ normalized to the SM inclusive $\sigma(pp \to H)$: 3.1 – 9.0 pb



Conclusions & Summary

- ATLAS is highly active in searching for BSM phenomena in the Higgs sector. Effort to cover maximum topologies.
- The Run 2 data are being analyzed. A lot of new results released this Summer.
- Shown selection of recent beyond Standard Model Higgs results
- No sign of additional Higgs boson seen in the LHC data yet. Therefore, exclusion limits are set.
- Looking forward to analyze data being collected this year