Searches for Higgs-like or diboson resonances with the ATLAS detector

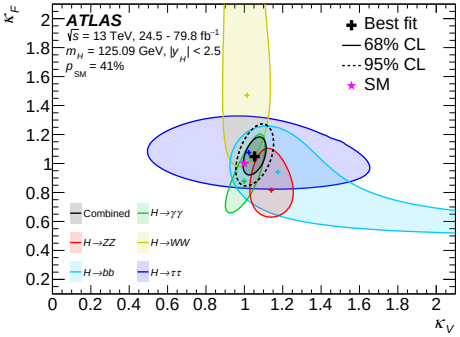
Joey Carter, on behalf of the ATLAS Collaboration

University of Toronto

April 14, 2021

Motivation: Multiple Higgs bosons?

- Measurements of the Higgs boson at the LHC have shown excellent agreement with Standard Model (SM) predictions:
  - ➜ Production cross sections, branching ratios, couplings to vector bosons and fermions.



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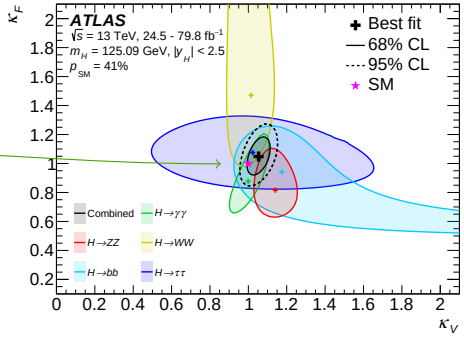

Phys. Rev. D **101** (2020) 012002

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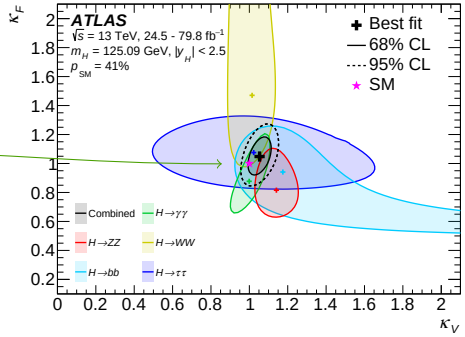

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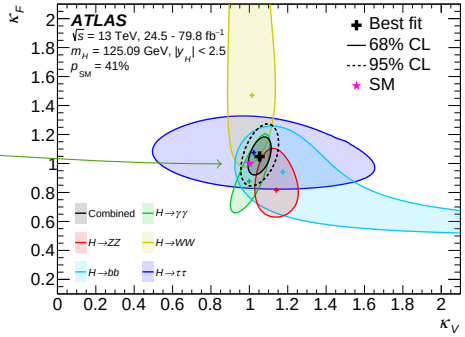

Many extensions of the Standard Model predict additional Higgs bosons

- For example, **Two-Higgs-Doublet models** (2HDM) predict 5 Higgs bosons: two neutral CP even (h, H), one CP odd (A) and two charged Higgs bosons ($H^{\pm}$).

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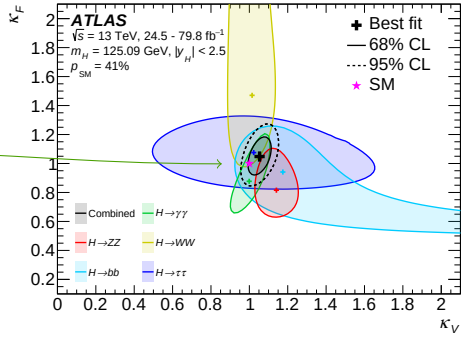

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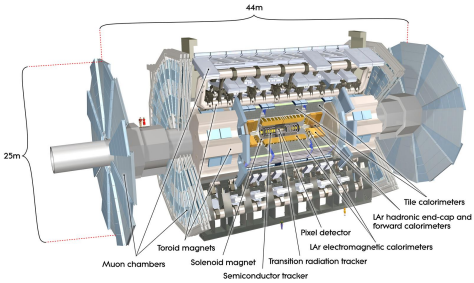
  - → The **Minimal Supersymmetric Standard Model** (MSSM) is one such 2HDM model.

The ATLAS Higgs-like search program



JINST **3** (2008) S08003

The ATLAS Experiment at the LHC

- General-purpose detector at the Large Hadron Collider.
- Recorded $139\,\text{fb}^{-1}$ of pp collision data at $\sqrt{s} = 13\,\text{TeV}$ during Run 2 of the LHC.
  - ➜ All analyses presented here use **full Run 2 dataset**.

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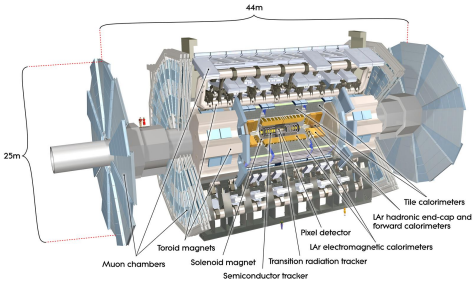

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- Precision measurements of SM Higgs couplings and reinterpretations in BSM extensions.
  - ➜ For example, searches for DM with interpretations in models with extended Higgs sector.

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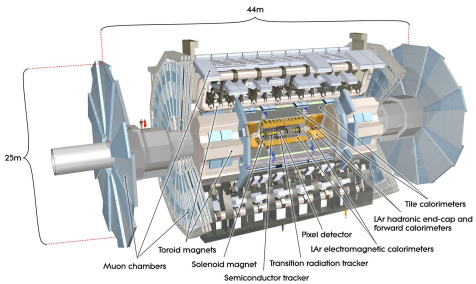

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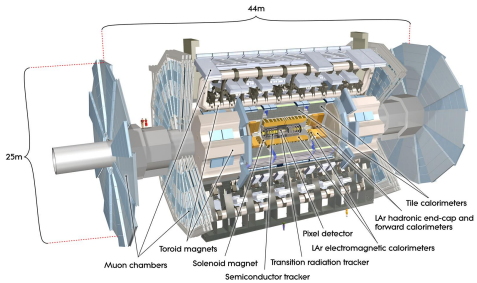

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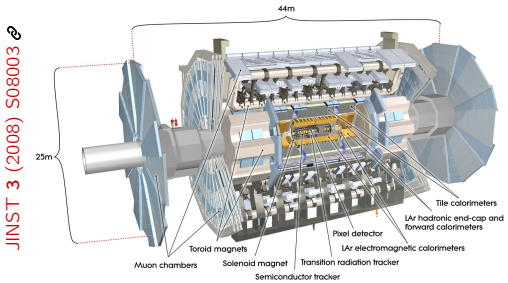

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Improvements from previous analyses

- Increased luminosity → larger dataset.
- Improved object reconstruction/isolation.
- Use of multivariate analysis (MVA) techniques.

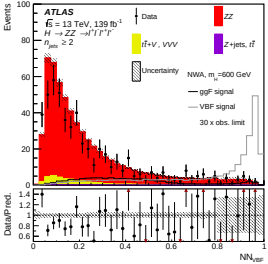
→

Searches for heavy ZZ resonances

arXiv: 2009.14791 [hep-ex]

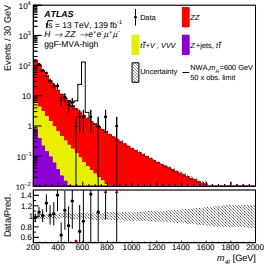
Search for heavy spin-0 resonance (e.g. heavy Higgs) and spin-2 gravition

- Combination of $\ell^+\ell^-\ell^+\ell^-$ and $\ell^+\ell^-\nu\bar{\nu}$ channels: benefit from mass resolution of 4ℓ and larger branching ratio of $\ell^+\ell^-\nu\bar{\nu}$.
- Improvements w.r.t. Eur. Phys. J. C **78** (2018) 293 from improved lepton reconstruction/isolation and use of particle-flow jets; improved event selection; use of Neural Network (NN) for event classification in 4ℓ channel.



$X \to ZZ \to \ell^+\ell^-\ell^+\ell^-$

- Select two same-flavour, opposite-sign lepton pairs ($\ell = e, \mu$).
- **Main background** from non-resonant ZZ ($\sim$97 %): shape modelled by empirical function, normalization allowed to vary freely in fit to data.
- Event categorization by **two separate neural networks**: one classifier for ggF and one for VBF:
  - → 5 event categories depending on lepton flavour and NN score.



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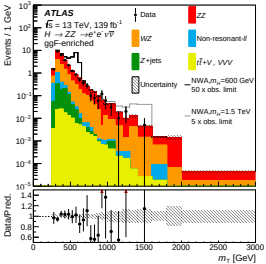
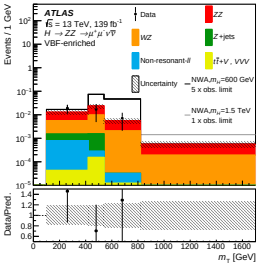
$X \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$

- Select one same-flavour, opposite-sign lepton pair + $E_{\mathrm{T}}^{\mathrm{miss}}$.
  - → Require $E_{\mathrm{T}}^{\mathrm{miss}} > 120\,\mathrm{GeV}$ and **high $E_{\mathrm{T}}^{\mathrm{miss}}$ significance**.
  - → Also require $E_{\mathrm{T}}^{\mathrm{miss}}$ to be back-to-back with lepton pair: $\Delta\phi(\vec{p}_{\mathrm{T}}^{\ell\ell}, \vec{E}_{\mathrm{T}}^{\mathrm{miss}}) > 2.5\,\mathrm{rad}$
- **Dominant backgrounds** from ZZ and WZ:
  - → ZZ from simulation with floating normalization.
  - → WZ estimated using data-driven method with 3-lepton control region.
- Full invariant mass cannot be reconstructed → use **transverse mass** as discriminating variable:

$$m_{\mathrm{T}} \equiv \sqrt{\left[\sqrt{m_Z^2 + \left(p_{\mathrm{T}}^{\ell\ell}\right)^2} + \sqrt{m_Z^2 + \left(E_{\mathrm{T}}^{\mathrm{miss}}\right)^2}\right]^2 - \left|\vec{p}_{\mathrm{T}}^{\ell\ell} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}}\right|^2}$$

- Use **cut-based approach** to categorize ggF-like and VBF-like events:
  - → VBF-like if $m_{jj} > 550\,\mathrm{GeV}$, $\Delta\eta_{jj} > 4.4$





Searches for heavy ZZ resonances

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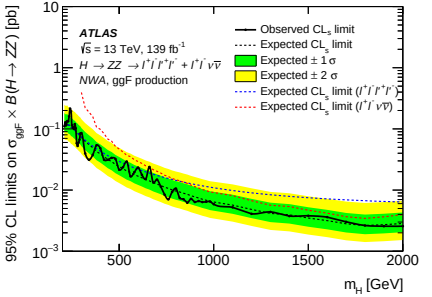
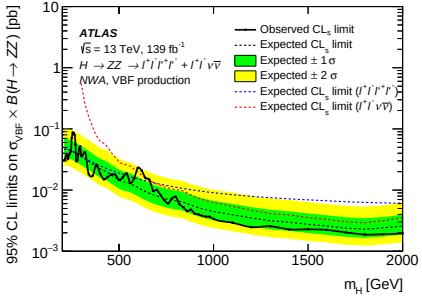
- Combine $\ell^+\ell^-\ell^+\ell^-$ and $\ell^+\ell^-\nu\bar{\nu}$ channels: **no significant excess observed**.
  - ➜ Set upper limits on $\sigma \times \mathrm{BR}(X \to ZZ)$.
- Narrow-width signals: fits for ggF and VBF processes done separately (while profiling the other process) to remain model independent, *i.e.* assume no relative production rate between the two.
- Large-width signals: interference effects between heavy and light Higgs, and Higgs/$gg \to ZZ$ considered.
- Interpretations also in 2HDM models and for a Randall-Sundrum graviton [see Backup].





Upper Limits (95 % CL)

ggF:

- 200 fb at 240 GeV
- 2.6 fb at 2000 GeV

VBF:

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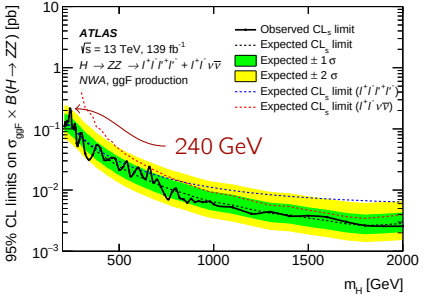

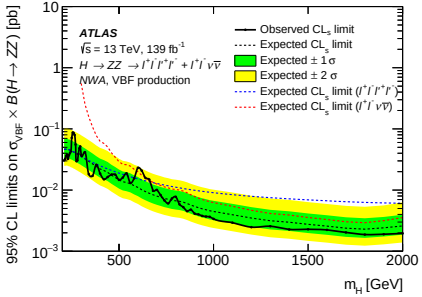

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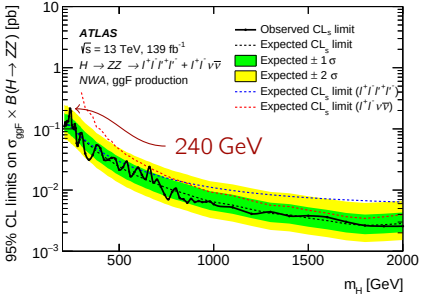

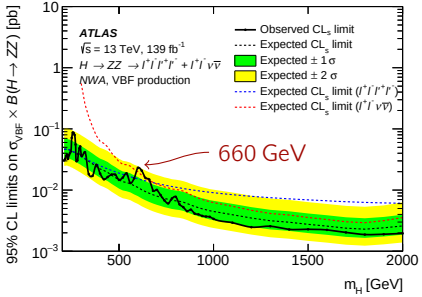

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Searches for heavy $\gamma\gamma$ resonances

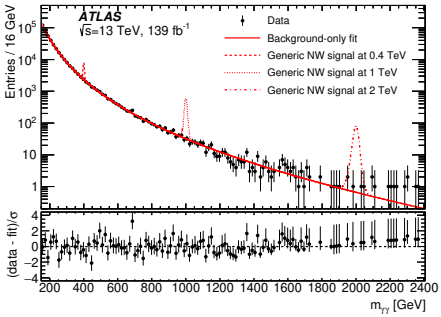
arXiv: 2102.13405 [hep-ex]

Search for heavy spin-0 resonance (e.g. heavy Higgs) and spin-2 gravition decaying to $\gamma\gamma$

- Improvements w.r.t. Phys. Lett. B **775** (2017) 105 from improved photon reconstruction/isolation; use of the functional decomposition method to assess the spurious signal uncertainty.

$X \to \gamma\gamma$

- Search for spin-0 and spin-2 resonances in photon-pair invariant mass spectrum.
- Select events with **two isolated photons** within acceptance of EM calorimeter. Same event selection for spin-0 and spin-2.
- Signal model: truth lineshape (relativistic Breit-Wigner) $\otimes$ detector resolution (double-sided crystal ball).
- Background model: template function built from simulated $\gamma\gamma$ events, and from a data control region for γ+jet events.



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- **No significant excess observed**. Largest excess at a mass of $m_{\gamma\gamma} = 684\,\text{GeV}$.
  - ➜ 3.29σ local significance (1.3σ global).
- Set upper limits on $\sigma_{\text{fid}} \times \text{BR}(X \to \gamma\gamma)$ for spin-0 case, $\sigma \times \text{BR}(G \to \gamma\gamma)$ for spin-2 case.
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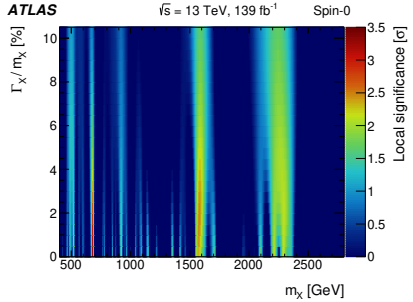

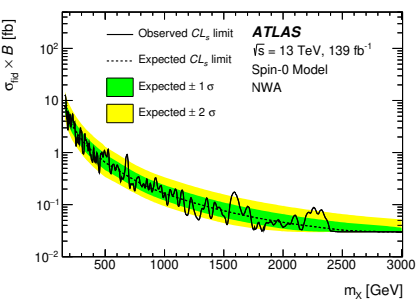

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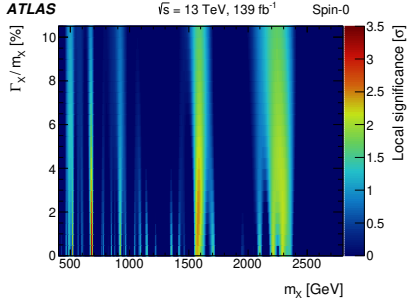

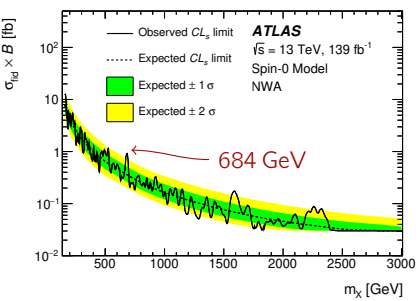

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Search for $A \to ZH$

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Search for a heavy neutral Higgs boson, A, decaying into a Z boson and another heavy Higgs boson, H

- Three channels considered (all with $Z \to \ell^+\ell^-$, where $\ell = e, \mu$):
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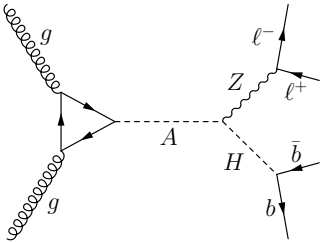

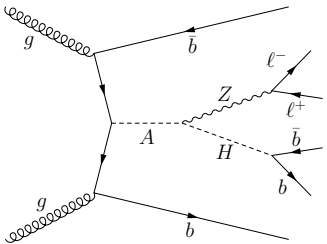

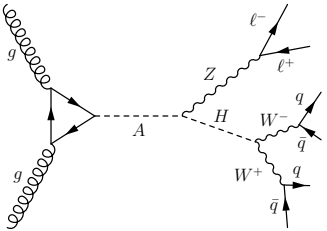

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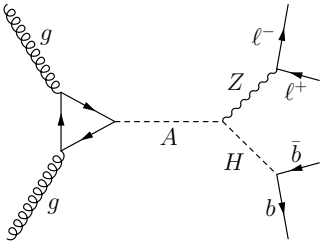

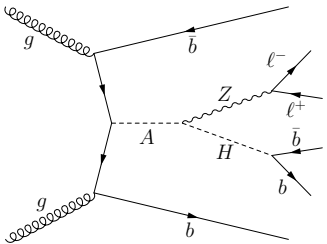

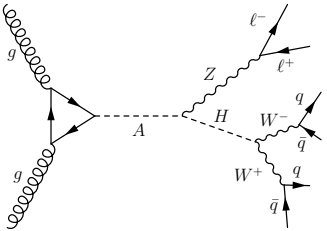

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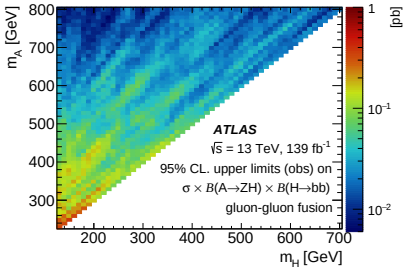
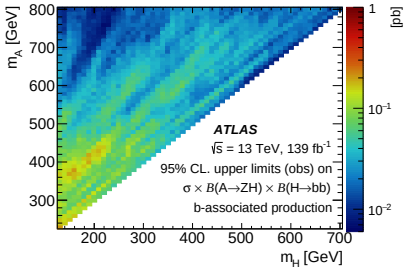
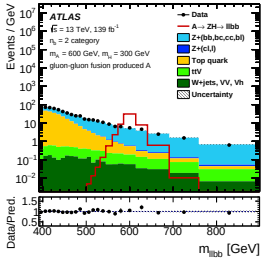
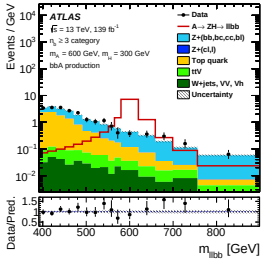
The $\ell^+\ell^- b\bar{b}$ final state

- Categorize production mechanism according to b-jet multiplicity:
  - → $n_b = 2$: ggF-like. Select $(0.85m_H - 20\,\text{GeV}) < m_{bb} < (m_H + 20\,\text{GeV})$.
  - → $n_b \geq 3$: bbA-like. Select $(0.85m_H - 25\,\text{GeV}) < m_{bb} < (m_H + 50\,\text{GeV})$.
- **Dominant background** (∼60–70 %) from Z+jets:
  - → Normalization from data-driven approach in control region defined by inverting the m_{bb} window criterion for each H boson mass hypothesis.







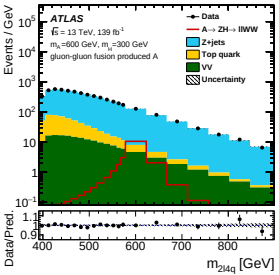


Search for $A \to ZH$

arXiv: 2011.05639 [hep-ex]

The $\ell^+\ell^- W^+(\to q\bar{q})W^-(\to q\bar{q})$ final state

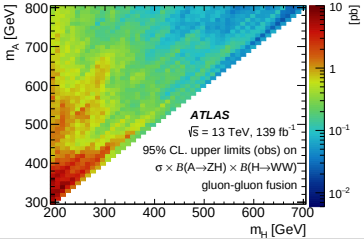
- Construct 4-jet system from five highest-p_T jets according to kinematic-variable cuts which optimize signal efficiency and background rejection.
- Select events with $m_H - 53\,\text{GeV} < m_{4q} < 0.97 m_H + 54\,\text{GeV}$.
- **Dominant background** (∼90 %) from Z+jets
  - ➜ Normalization from inverted-m_{4q} control region.



No significant excess observed in either channel

➜ **Largest excesses** and **upper limits** (2HDM interpretations in Backup):

Channel	(m_A, m_H) [GeV]	Local (Global) Significance	Upper Limits (95 % CL)
$\ell^+\ell^- b\bar{b}$ (ggF)	(610, 290)	$3.1(1.3)\sigma$	6.2 to 380 fb
$\ell^+\ell^- b\bar{b}$ (bbA)	(440, 220)	$3.1(1.3)\sigma$	6.8 to 210 fb
$\ell^+\ell^- W^+W^-$ (ggF)	(440, 310)	$2.9(0.82)\sigma$	23 to 8900 fb

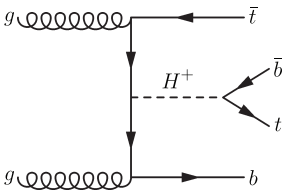


Search for $H^{\pm} \to tb$

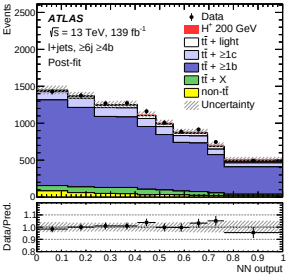
arXiv: 2102.10076 [hep-ex]

Search for a charged Higgs boson decaying into a top and bottom quark

- In 2HDM with $\cos(\beta - \alpha) \sim 0$, dominant decay is $H^+ \to tb$ for $m_{H^+} > 200$ GeV.
- Improvements w.r.t. JHEP **03** (2016) 127 from improved object reconstruction/isolation; use of simultaneous fit to MVA classifier outputs to determine signal contribution and background normalization.



- Split into categories with different jet and b-jet multiplicities: (5 jets + 3 or ≥ 4 b-jet, ≥ 6 jets + 3 or ≥ 4 b-jets).
- Simulation-based modelling of top-related backgrounds does not agree with data $\to$ apply **reweighting procedure** based on jet multiplicity and H_T distributions. ($H_T \equiv$ scalar sum of p_T of the lepton and all jets.)
- **Neural network** trained on parameters related to jet and lepton kinematics (e.g. jet p_T, scalar sum of the p_T of all jets, jet and lepton centrality), and a *kinematic discriminant* (itself an MVA).



Search for $H^{\pm} \to tb$

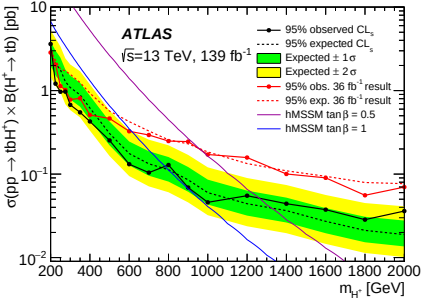
arXiv: 2102.10076 [hep-ex]

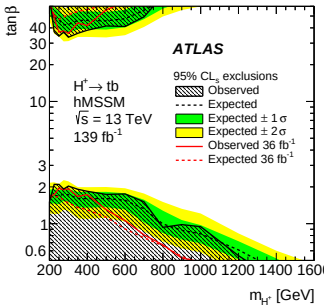
No significant excess observed.

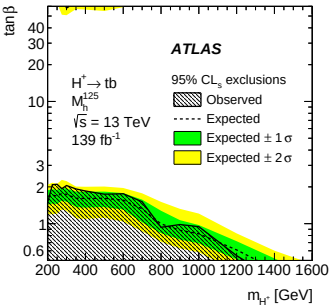
- Set upper limits on $\sigma \times BR(H^{+} \to tb)$.
- Interpretations in hMSSM and different M_h^{125} scenarios.

Upper Limits (95 % CL)

- 3.6 pb at $m_{H^+} = 200$ GeV
- 0.036 pb at $m_{H^+} = 2000$ GeV







Search for doubly-charged Higgs bosons

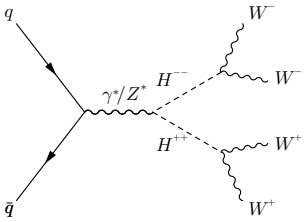
arXiv: 2101.11961 [hep-ex]

Search for doubly- and singly-charged Higgs bosons decaying into vector bosons

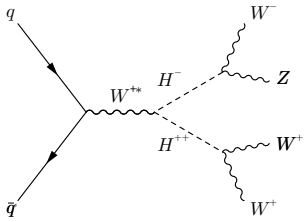
- Doubly-charged Higgs bosons appear in models which account for neutrino masses, such as the type-II seesaw mechanism.
- Improvements w.r.t. Eur. Phys. J. C **79** (2019) 58: include the production of a $H^{\pm\pm}$ boson in association with a $H^{\pm}$ boson.

Two scenarios considered

- Take triplet vacuum expectation value $v_t = 100\,\text{MeV}$ such that only possible decay is $H^{\pm\pm} \to W^{\pm}W^{\pm}$.
- Only consider $H^{\pm} \to W^{\pm}Z$: depending on $H^{\pm}$ mass, branching ratio varies between 40 % and 60 %.
  - → Contribution from other possible $H^{\pm}$ decays in SR found to be negligible.



(a) $m_{H^{\pm}} - m_{H^{\pm\pm}} > 100\,\text{GeV}$

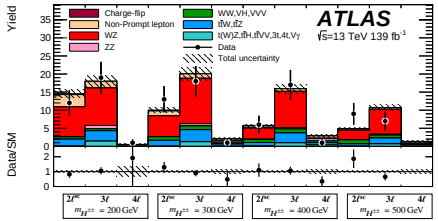


(b) $m_{H^{\pm}} - m_{H^{\pm\pm}} < 5\,\text{GeV}$

Search for doubly-charged Higgs bosons

arXiv: 2101.11961 [hep-ex]

- Three mutually-exclusive channels considered:
  - → Two same-charged leptons ($2\ell^{SC}$)
  - → Three leptons (3ℓ)
  - → Four leptons (4ℓ)
- **Dominant backgrounds** (depending on channel) from $WZ/ZZ/WW$ production, non-prompt leptons, $t\bar{t}W/t\bar{t}Z$.
  - → Data-driven methods used for many of these backgrounds in dedicated CRs (e.g. WZ and non-prompt backgrounds).
- **No significant excess observed**: set upper limits on $\sigma \times$ BR.



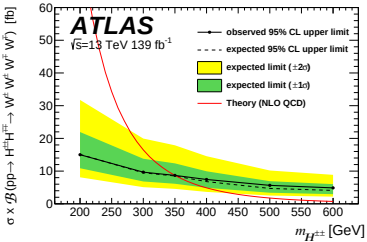
Upper Limits (95 % CL)

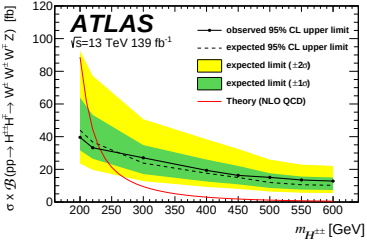
Pair production:

- 15 to 5 fb

Associated production:

- 40 to 20 fb





→

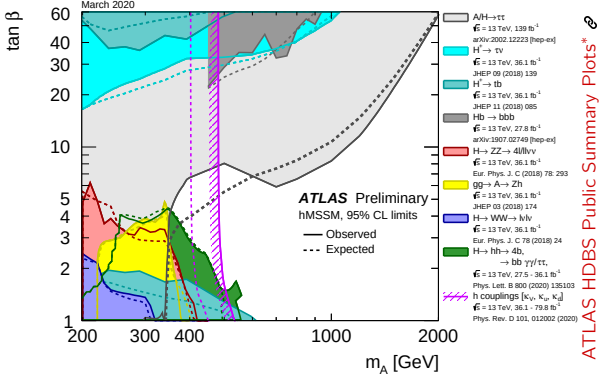
Summary

No significant excess over SM predictions

- ATLAS has an active BSM-Higgs and diboson-resonance search programme.
- Substantial update of constraints on 2HDM and other BSM models.
- Only small subset of results shown today: still many exciting new regions of phase space to probe using the full Run 2 dataset.

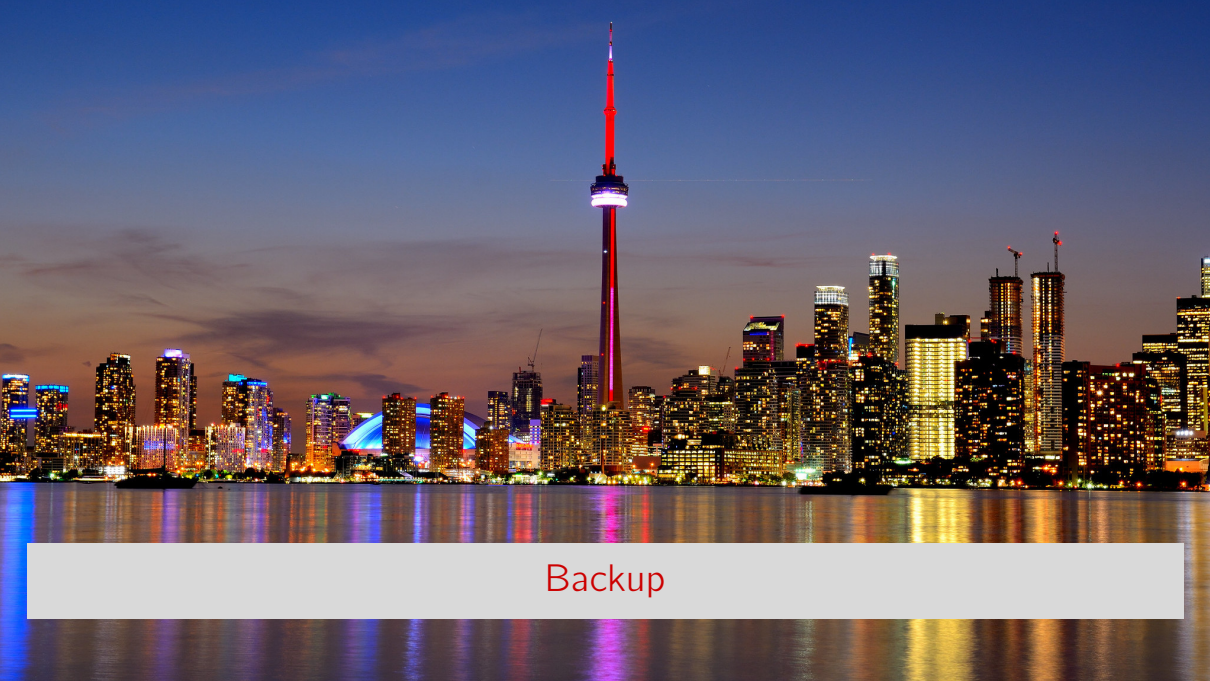
See L. D'Eramo's talk for latest results on $X \to HH$ searches!

Combination Example: hMSSM



*As of March 2020: many new results still to add

Latest ATLAS results at https://twiki.cern.ch/twiki/bin/view/AtlasPublic



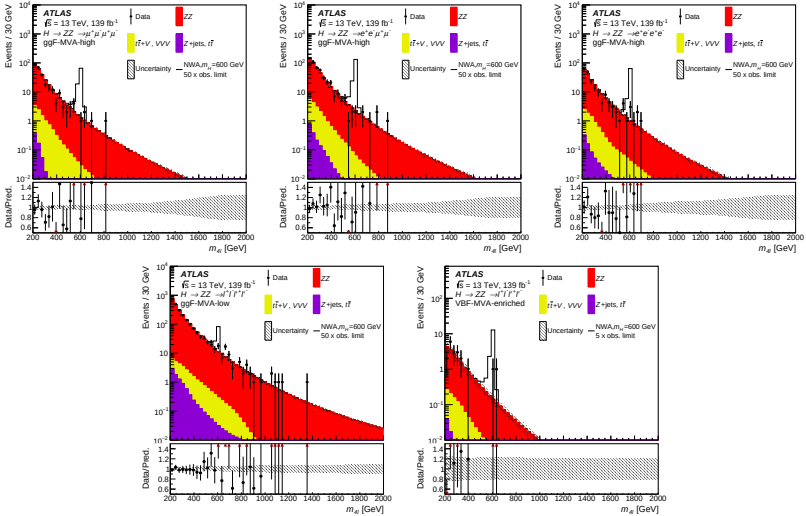
Backup

Searches for heavy ZZ resonances

HIGG-2018-09

$\ell^+\ell^-\ell^+\ell^-$ Distributions

- Distributions of the four-lepton invariant mass $m_{4\ell}$ in each of the five event categories in the $\ell^+\ell^-\ell^+\ell^-$ channel.

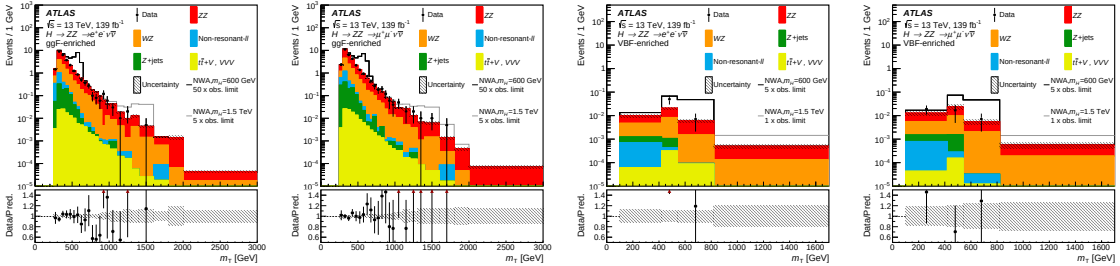


Searches for heavy ZZ resonances

HIGG-2018-09

$\ell^+\ell^-\nu\bar{\nu}$ Distributions

- Distributions of the transverse mass m_{T} in each of the four event categories in the $\ell^+\ell^-\nu\bar{\nu}$ channel.

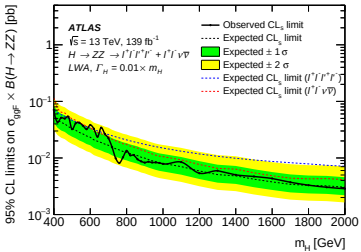


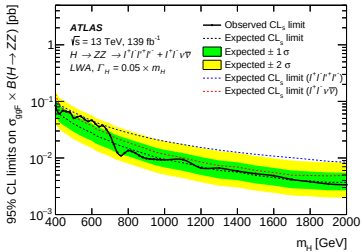
Searches for heavy ZZ resonances

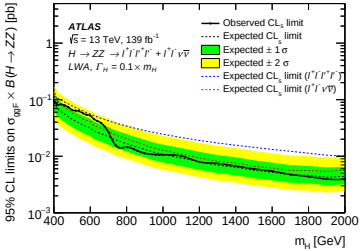
HIGG-2018-09

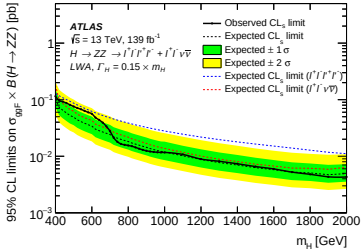
Large-width spin-0 Interpretations

- 95 % CL upper limits on $\sigma_{\text{ggF}} \times \text{BR}(H \to ZZ)$ as a function of m_H assuming a width of 1, 5, 10 and 15 % of m_H.







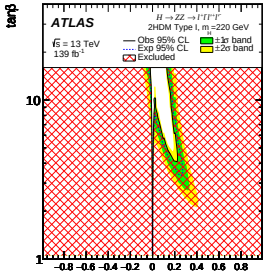


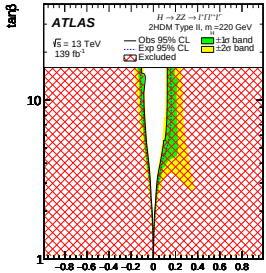
Searches for heavy ZZ resonances

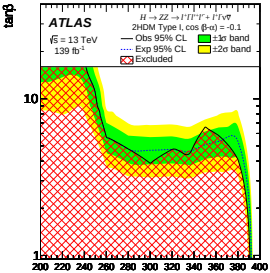
HIGG-2018-09

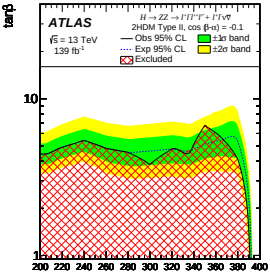
2HDM Interpretations

- Exclusion contour in the Type-I and Type-II 2HDM models:
  - → As a function of the parameters $\cos(\beta-\alpha)$ and $\tan\beta$, with $m_H = 220$ GeV
  - → As a function of m_H and $\tan\beta$, with $\cos(\beta-\alpha) = -0.1$







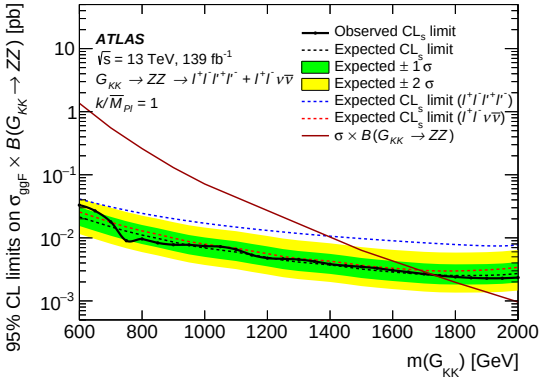


Searches for heavy ZZ resonances

HIGG-2018-09

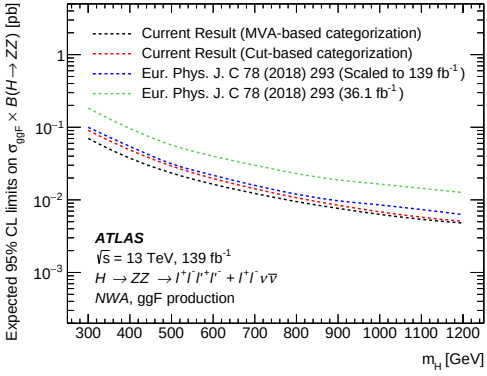
RS Graviton Interpretations

- 95 % CL upper limits on $\sigma \times \mathrm{BR}(G_{\mathrm{KK}} \to ZZ)$ for a KK graviton produced with $k/\bar{M}_{Pl} = 1$.



Analysis Improvements

- Improvements on the expected 95 % CL upper limits w.r.t. previous and cut-based analyses.

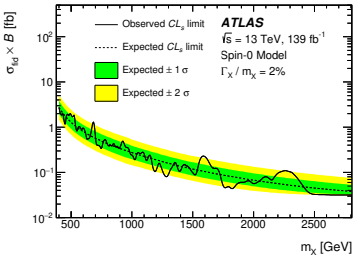


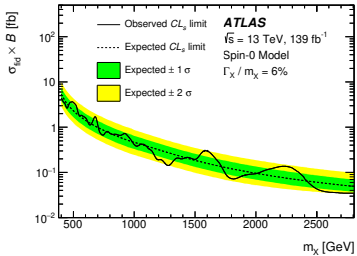
Searches for heavy $\gamma\gamma$ resonances

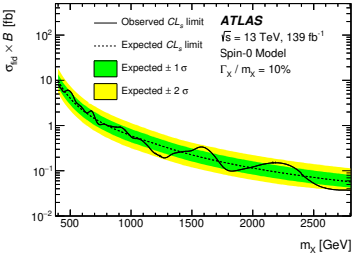
HIGG-2018-27

Large-width spin-0 Interpretations

- 95 % CL upper limits on $\sigma_{\text{fid}} \times \text{BR}(X \to \gamma\gamma)$ as a function of m_H assuming a width of 2, 6 and 10 % of m_X.





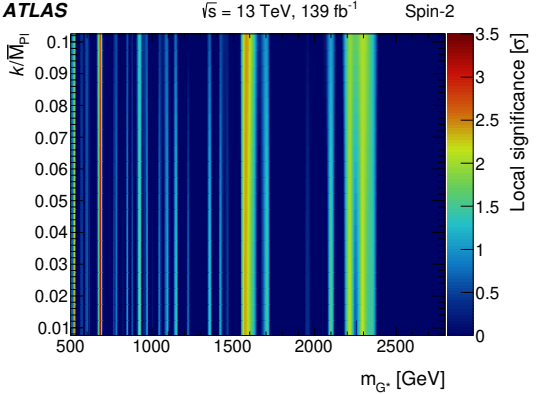


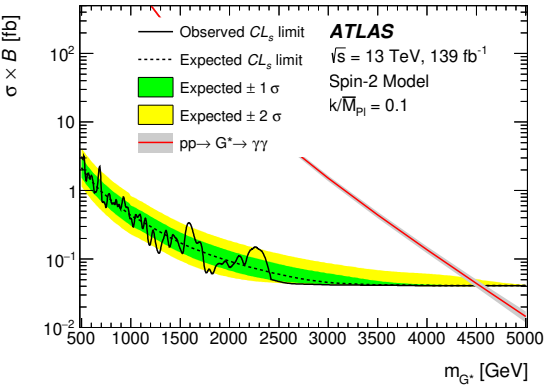
Searches for heavy $\gamma\gamma$ resonances

HIGG-2018-27

RS Graviton Interpretations

- Local significance in the spin-2 search as a function of the assumed signal mass m_{G^*} and $k/\bar{M}_{Pl}$.
- 95 % CL upper limits on $\sigma \times \mathrm{BR}(G_{KK} \to \gamma\gamma)$ with $k/\bar{M}_{Pl} = 0.1$.



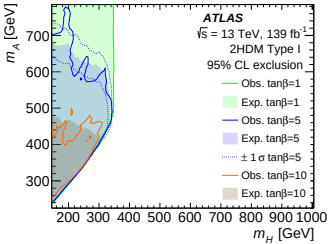


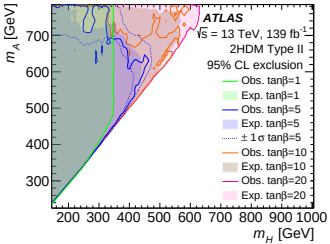
Search for $A \to ZH$

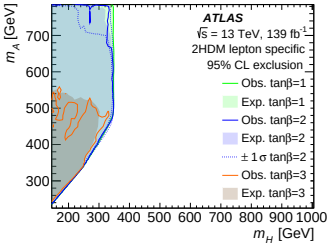
HDBS-2018-13

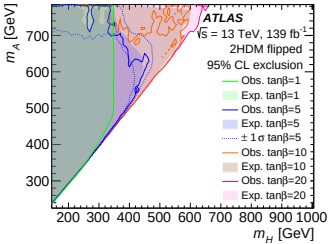
2HDM Interpretations

- 95 % CL exclusion regions for the $\ell^+\ell^- b\bar{b}$ channel in the (m_H, m_A) plane for various 2HDM scenarios and various $\tan\beta$ values.







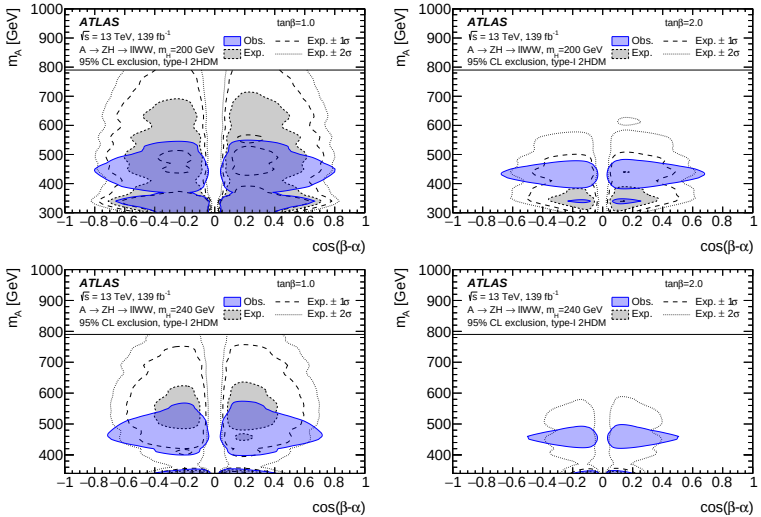


Search for $A \to ZH$

HDBS-2018-13

2HDM Interpretations

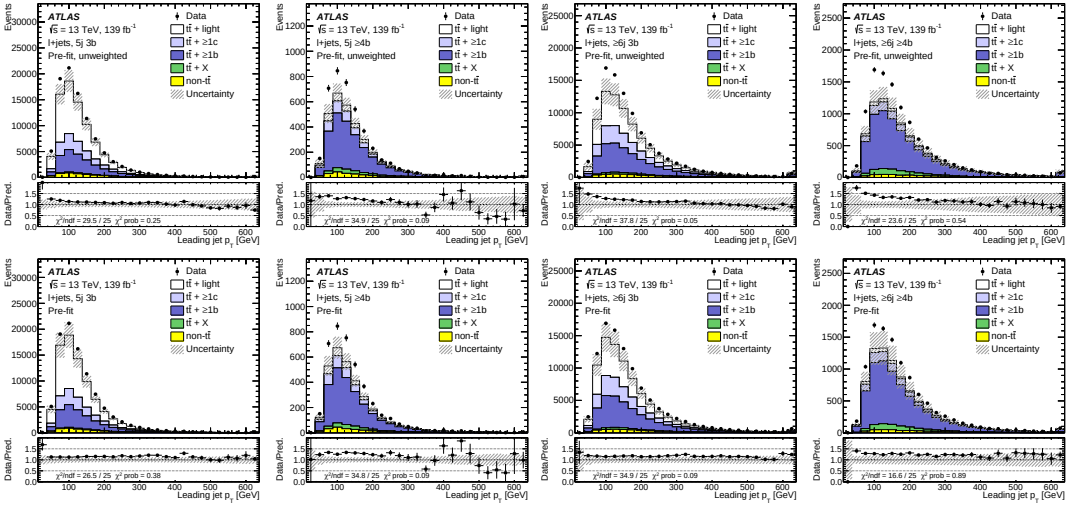
- 95 % CL exclusion regions for the $\ell^+\ell^- W^+W^-$ channel in the $(\cos(\beta-\alpha), m_A)$ plane for various $\tan\beta$ and m_H values.



Search for $H^+ \to tb$

HDBS-2018-51

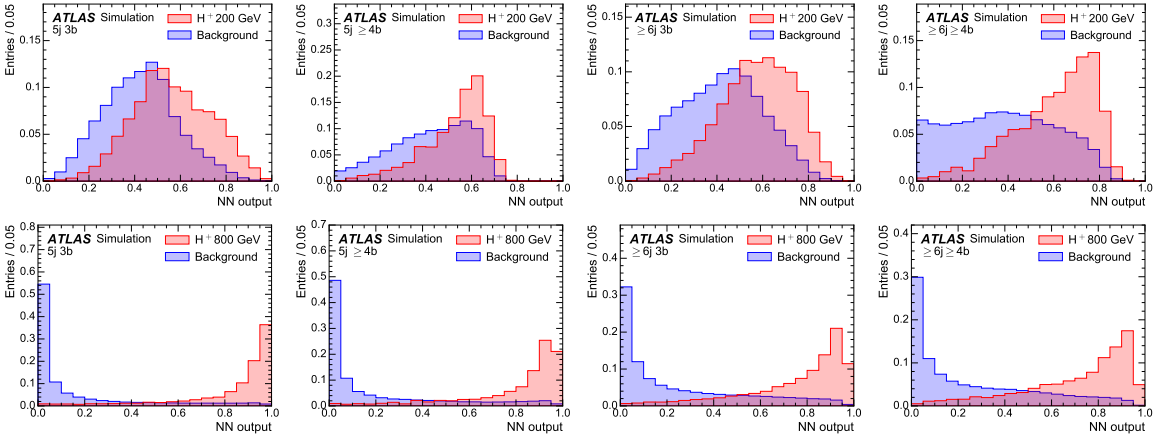
Leading jet p_T distributions: Pre-fit; before (top) and after (bottom) the reweighting was applied.



Search for $H^+ \to tb$

HDBS-2018-51

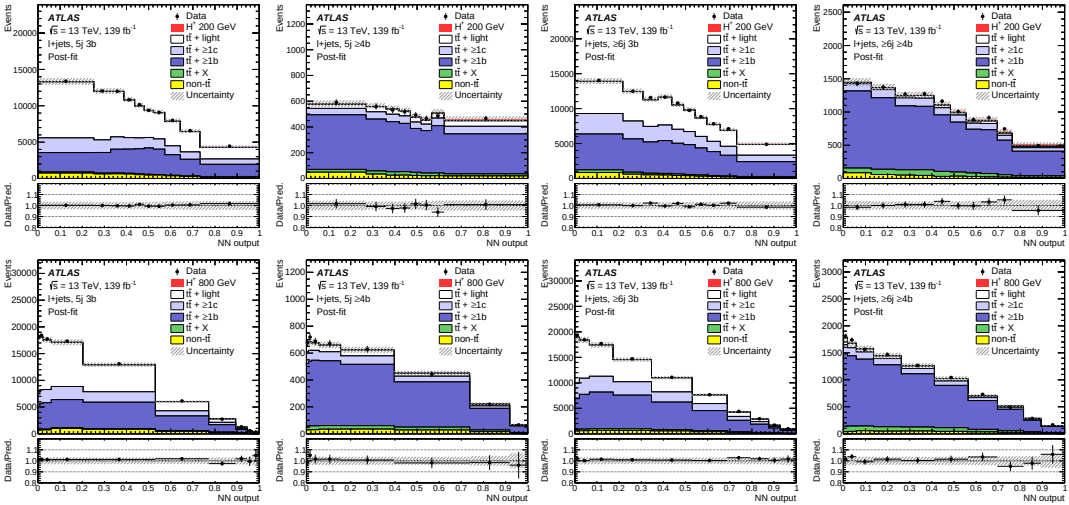
Expected NN output distributions: $m_{H^+} = 200\,\text{GeV}$ (top) and 800 GeV (bottom).



Search for $H^+ \to tb$

HDBS-2018-51

Observed NN output distributions: $m_{H^+} = 200\,\text{GeV}$ (top) and $800\,\text{GeV}$ (bottom).

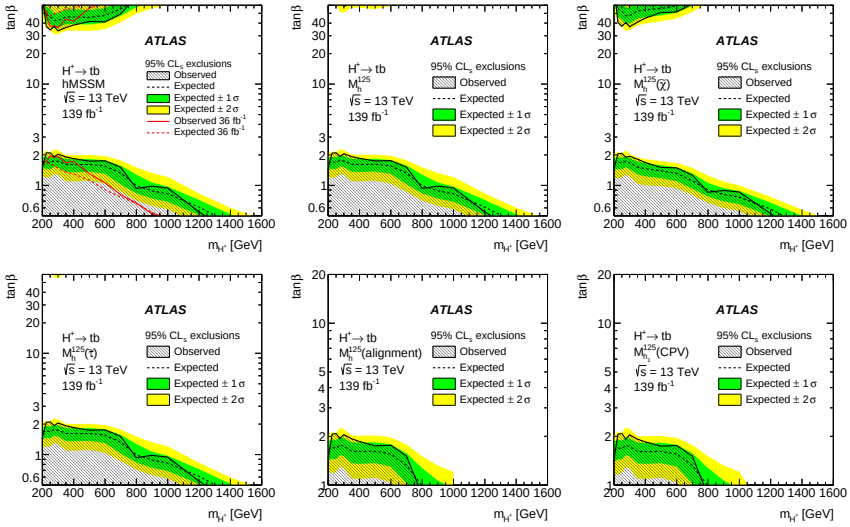


Search for $H^+ \to tb$

HDBS-2018-51

Interpretations

- 95 % CL exclusion limits on $\tan\beta$ as a function of m_{H^+} for the hMSSM and various M_h^{125} scenarios.

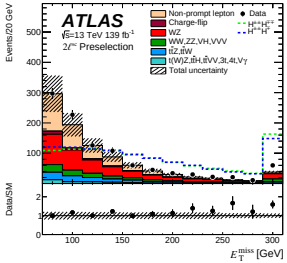


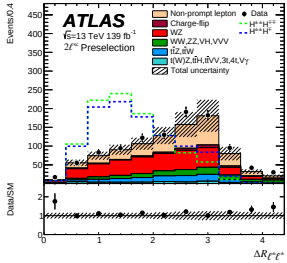
Search for $H^{++} \to WW$

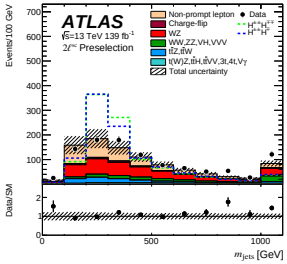
HDBS-2019-06

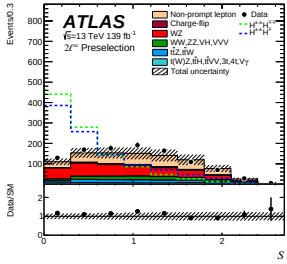
$2\ell^{SC}$ Signal Region

- Distribution of selected variables used to define the $2\ell^{SC}$ signal regions.







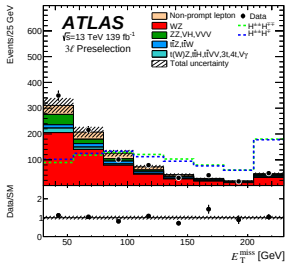


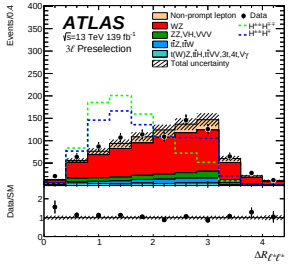
Search for $H^{++} \to WW$

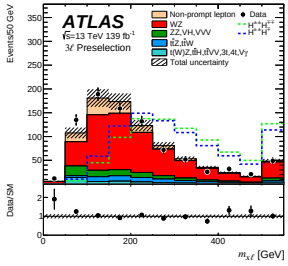
HDBS-2019-06

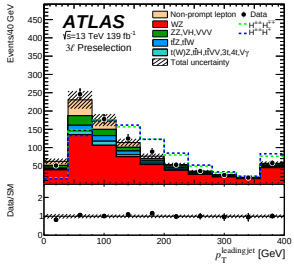
3ℓ Signal Region

- Distribution of selected variables used to define the 3ℓ signal regions.







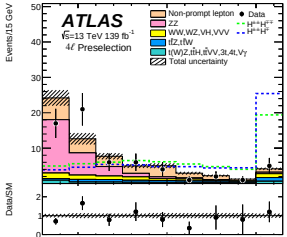


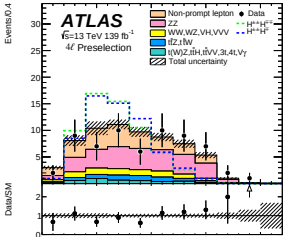
Search for $H^{++} \to WW$

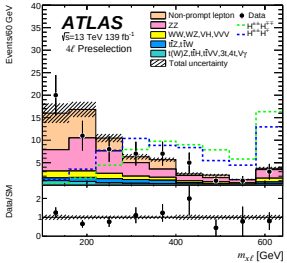
HDBS-2019-06

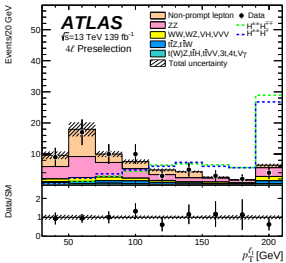
4ℓ Signal Region

- Distribution of selected variables used to define the 4ℓ signal regions.







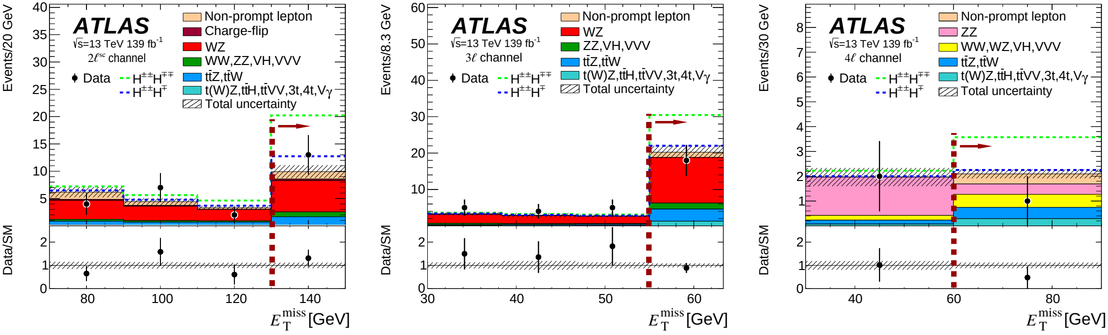


Search for $H^{++} \to WW$

HDBS-2019-06

$E_{\mathrm{T}}^{\mathrm{miss}}$ Distributions

- The $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution for the SRs of the $m_{H^{\pm\pm}} = 300$ GeV signal mass hypothesis, where the selection requirement on $E_{\mathrm{T}}^{\mathrm{miss}}$ has been removed.
- The last bin, isolated by a vertical red dashed line, is inclusive and corresponds to the SR.



Search for $X \to HH \to b\bar{b}\gamma\gamma$

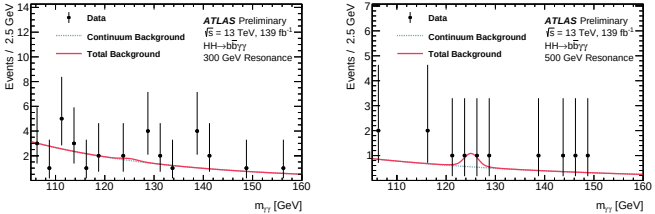
ATLAS-CONF-2021-016

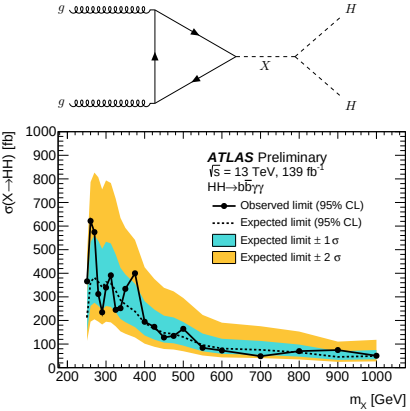
Search for heavy resonances decaying to a pair of Higgs bosons in the $b\bar{b}\gamma\gamma$ final state

- Improvements w.r.t. JHEP **11** (2018) 040.

- Uses two BDTs to separate resonant signals from di-photon and single Higgs.
  - → Combine BDT scores in quadrature and reweight event-by-event to give same $m^*_{b\bar{b}\gamma\gamma}$ as background.

- **No significant excess observed**.





For more on ATLAS di-Higgs searches, see L. D'Eramo's talk.