Search for exotic decays of the Higgs boson and additional scalar particles in ATLAS

Christopher Hayes (University of Michigan)
on behalf of the ATLAS collaboration

Lake Louise
Winter Institute 2022

February 20 - 26, 2022

Searches for BSM Higgs at the LHC

C. Hayes

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- After the discovery of the Higgs boson at 125 GeV: what is the nature of the Higgs sector? Is it completely SM or are new interactions waiting to be discovered?
- Extended Higgs sectors predicted by many theories of beyond the Standard Model physics, especially theories with naturalness, axions, SUSY, or dark matter.
- New light ($m_X < m_H/2$) states could appear in exotic decays of the 125 GeV Higgs boson, with current model-dependent constraint from fits to SM Higgs couplings being around Br(H→BSM) < ~25% [1].
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Newest ATLAS results highlighted in this talk (all full Run-2 dataset results):

Higgs to light resonances

- $ZH \to \ell\ell bb + \text{MET}$
- $H \to XX/ZX \to 4\ell$
- $H \to aa \to bb\mu\mu$

Charged Higgs in $t\bar{t}$

- $H^{\pm} \to cb$
- $H^{\pm} \to aW^{\pm}, a \to \mu\mu$

High-Mass

- $H \to \gamma\gamma$

ATLAS EXPERIMENT

[1] ATLAS-CONF-2021-053

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ATLAS EXPERIMENT

[1] ATLAS-CONF-2021-053

$ZH, Z \to \ell\ell, H \to bb$ + MET

C. Hayes

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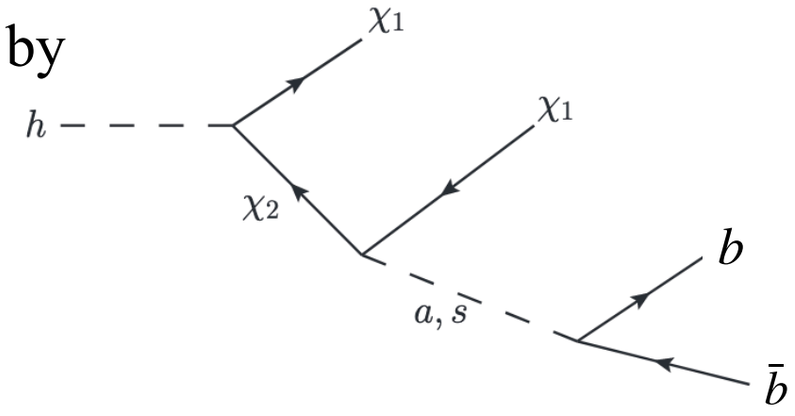
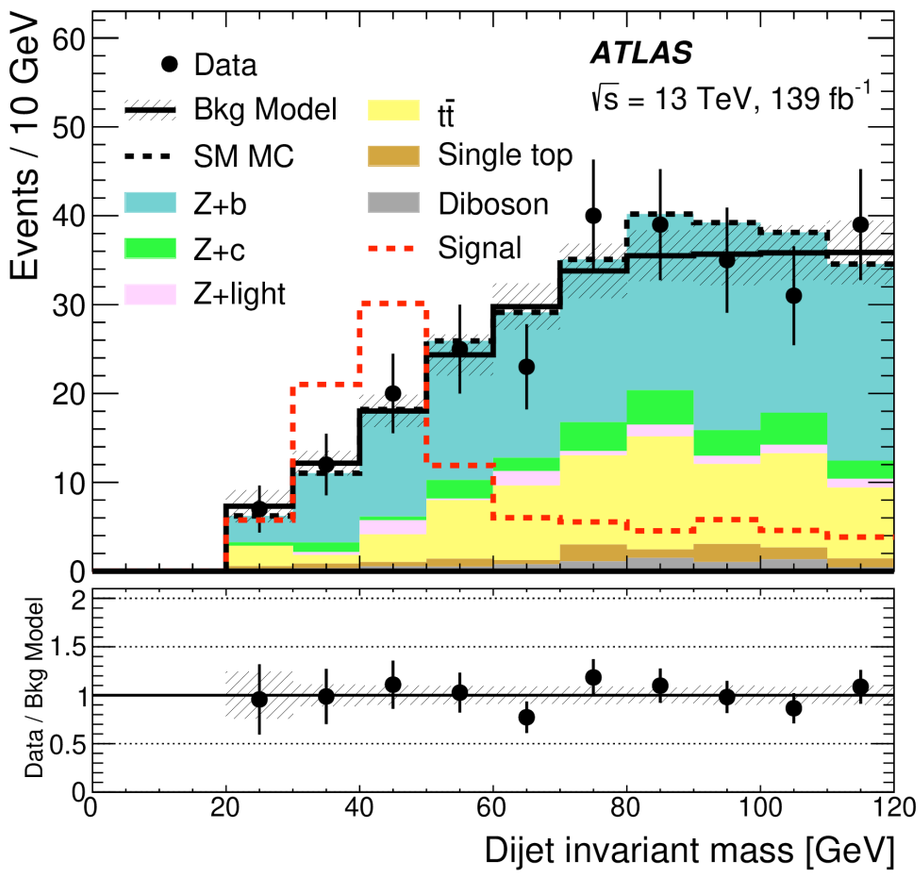
- Search for cascade decay $H \to \tilde{\chi}_2^0 \tilde{\chi}_1^0 \to (a \to bb)\ \tilde{\chi}_1^0 \tilde{\chi}_1^0$, predicted by NMSSM models, in ZH production
- Events required to have at least 2 jets (1 b-tagged jet), $E_{\mathrm{T}}^{\mathrm{miss}} > 100$ GeV, and p_{T} fraction cut to suppress top backgrounds.
- Main bkg contributions derived from Z and $t\bar{t}$ enhanced regions.
- Fit performed on dijet mass m_{jj} . No significant excess seen and limits set on several $(m_{\tilde{\chi}_1}, m_{\tilde{\chi}_2})$ benchmark points as a function of m_a

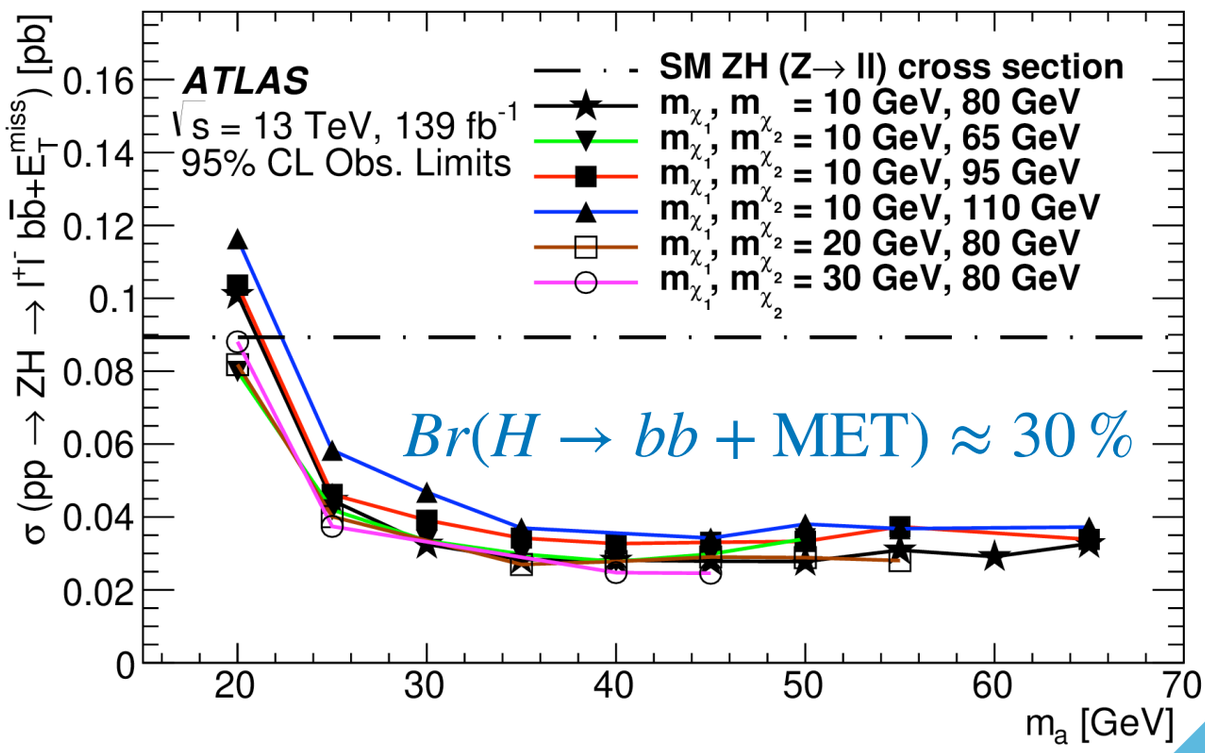


$$0.8 < \frac{p_{\mathrm{T}}^{jj} + E_{\mathrm{T}}^{\mathrm{miss}}}{p_{\mathrm{T}}^{\ell\ell}} < 1.2$$



First result in this channel from LHC!

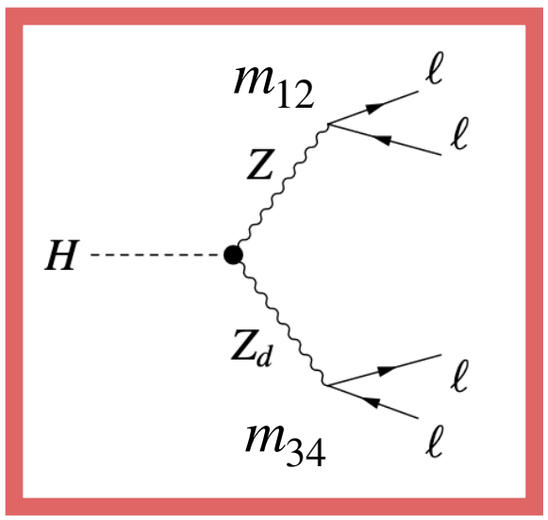
JHEP 01 (2022) 063



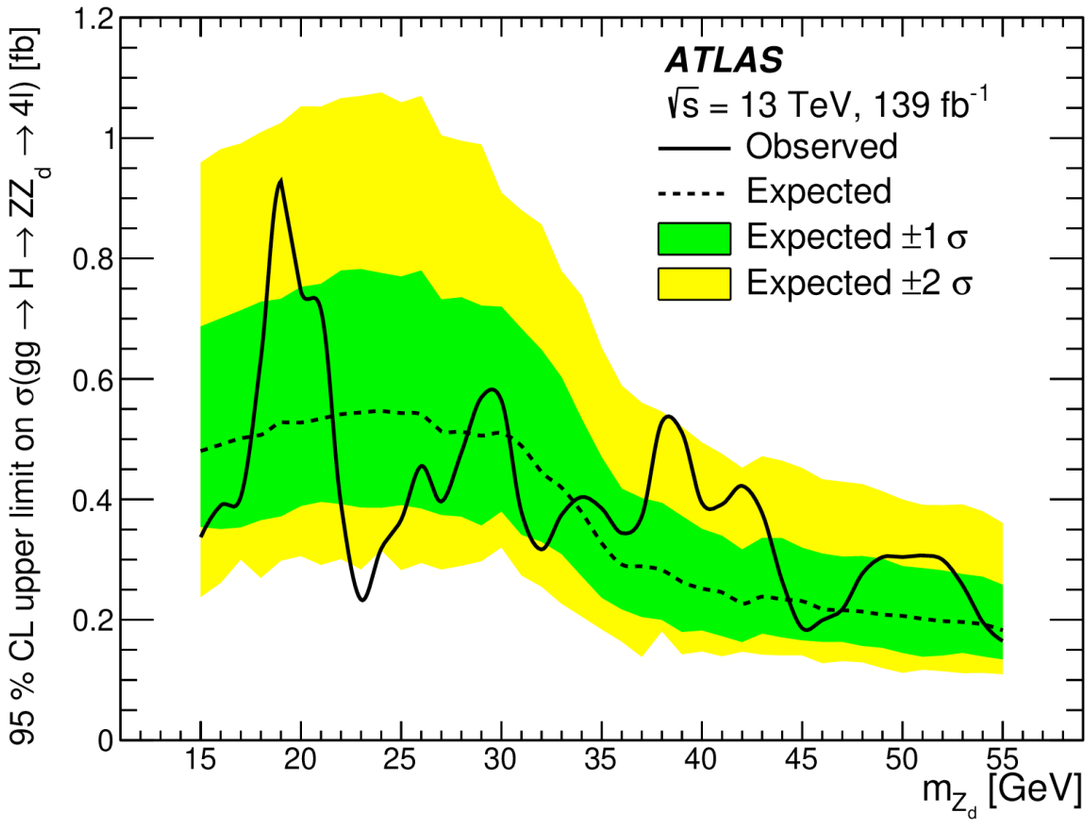
$H \to ZX \to 4\ell$

C. Hayes

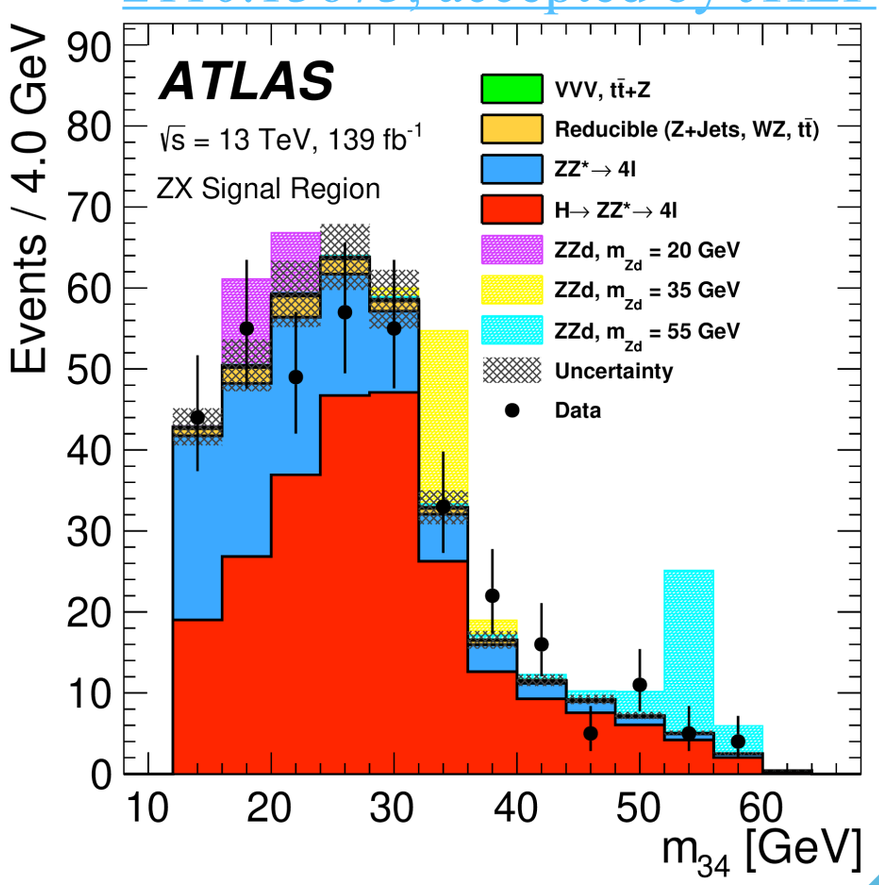
- Searches for new $U(1)_D$ gauge boson in Higgs decays with a Z boson, targeting both on-shell and off-shell region.



- Select 4 leptons (e, μ), one pair consistent with m_Z $50 < m_{12} < 102$ GeV, $m_{4\ell} \approx m_H \pm 5$ GeV.
- Main bkgs (ZZ^*, $H \to ZZ^*$) estimated by simulation and validated in $m_{4\ell}$ sidebands.
- Search for excess in lower mass pair $15 < m_{34} < 55$ GeV.
- No significant excess observed. Improves limits ~2x over previous analysis



2110.13673, accepted by JHEP



$H \to XX \to 4\ell$

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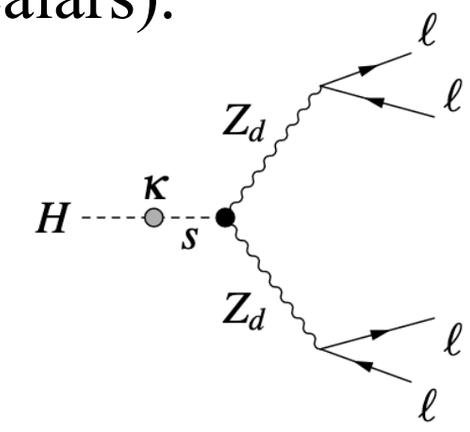
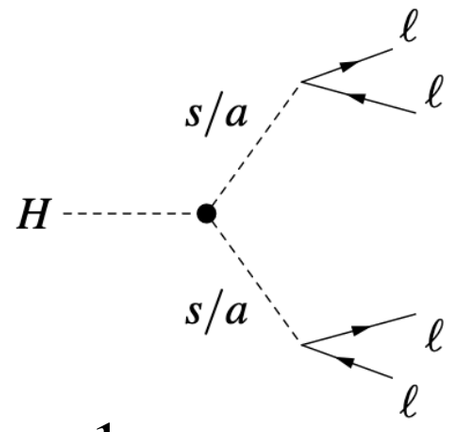
- Searches for pair of new low mass $U(1)_D$ gauge bosons (scalars) in the 4 lepton final state (4μ for scalars).

- Select 4 leptons (e, μ), $m_{4\ell} \approx m_H$.
  Require mass compatibility between pairs
  $m_{12}/m_{34} > 0.85$

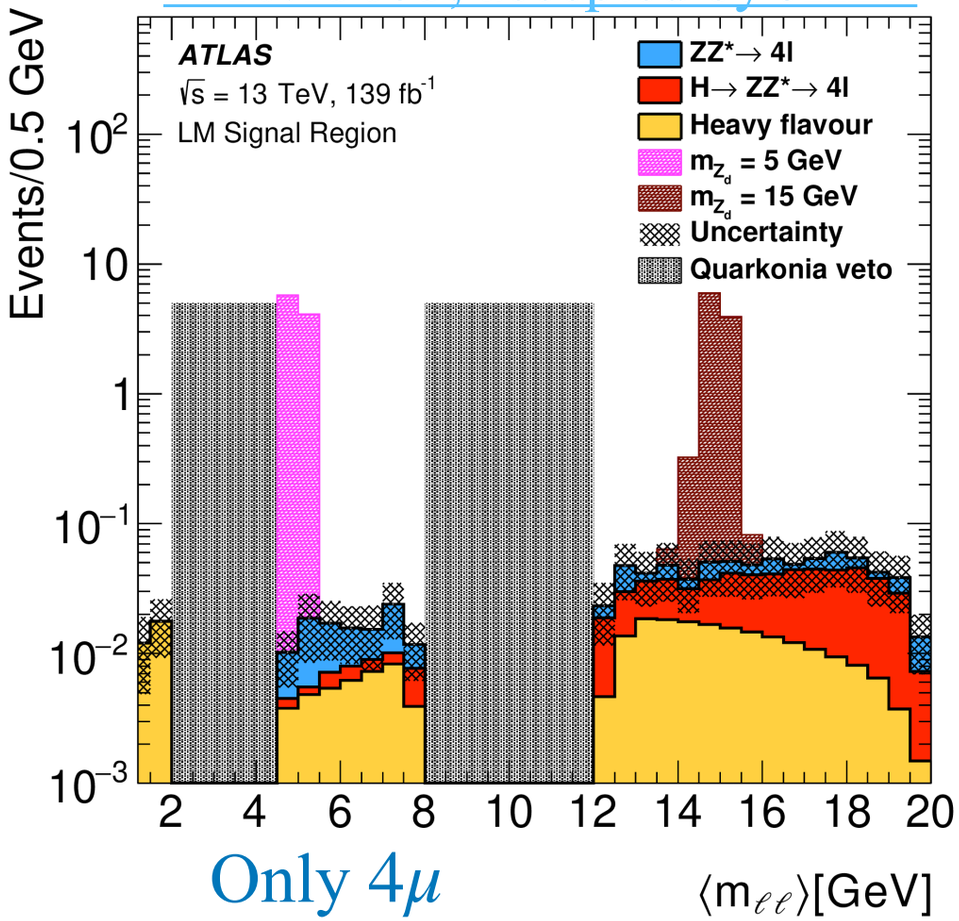
- Veto events with any pairings consistent with quarkonia and mis-paired Z boson.



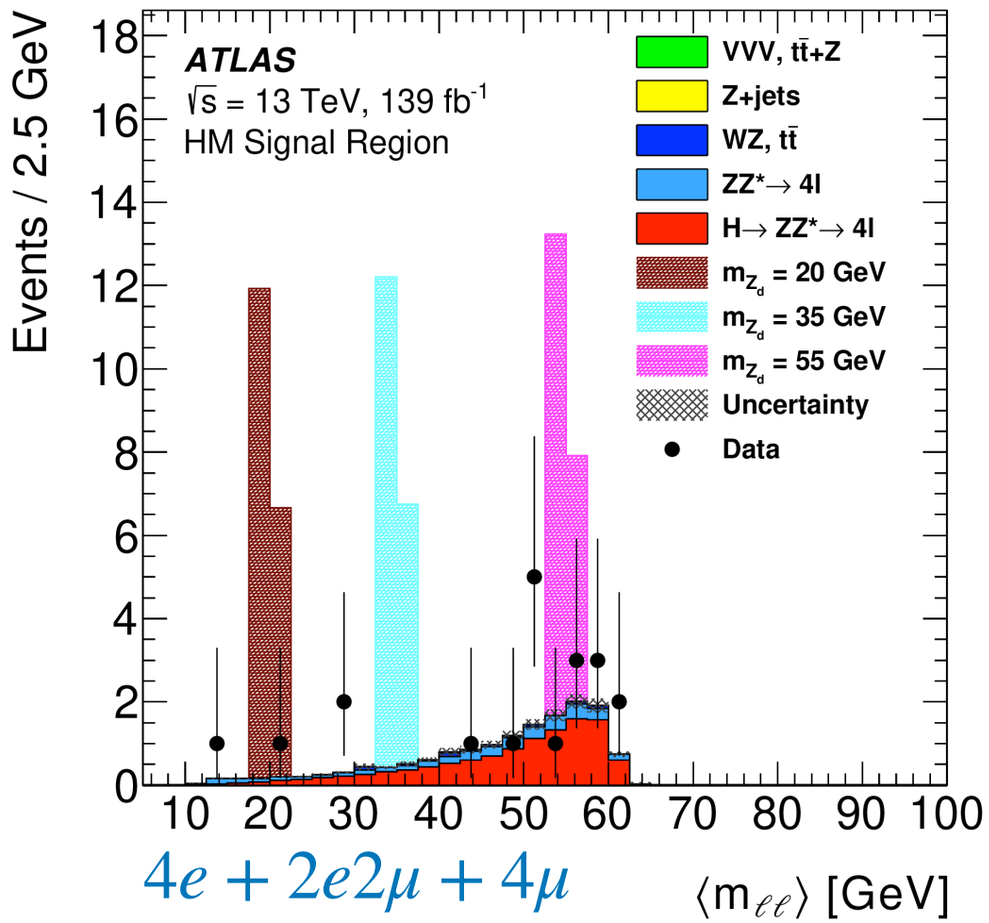


Fit average mass $< m_{\ell\ell} > = \frac{1}{2}(m_{12} + m_{34})$

2110.13673, accepted by JHEP



Only 4μ



$4e + 2e2\mu + 4\mu$

$H \to XX \to 4\ell$

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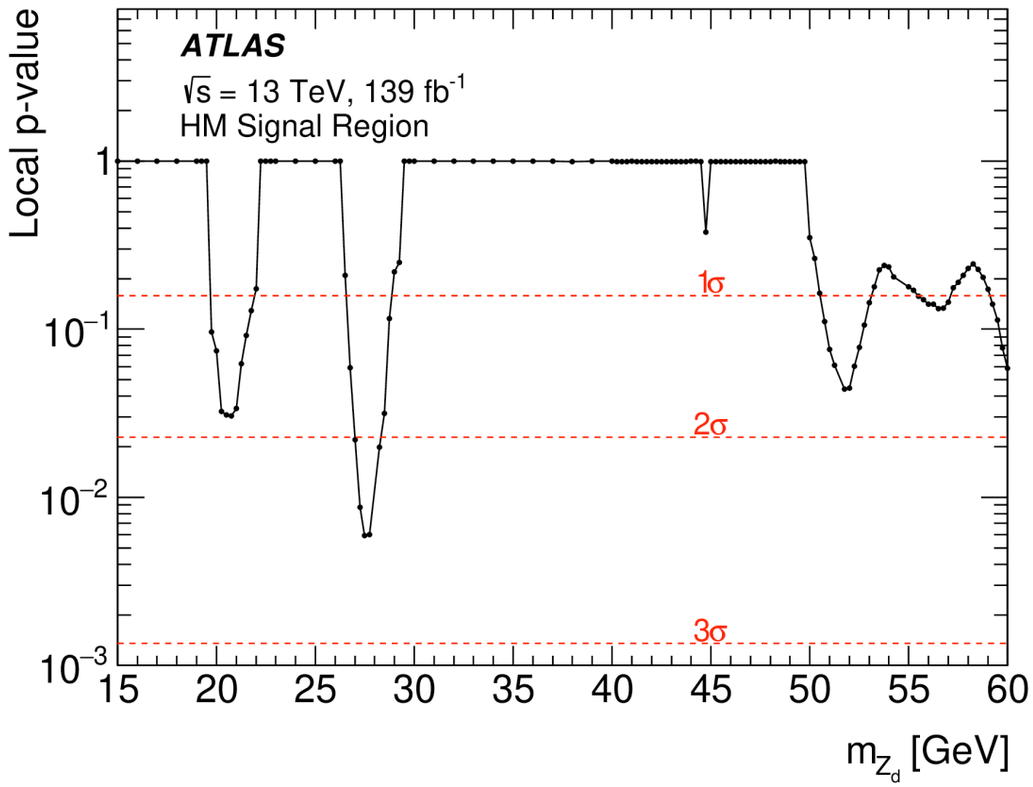
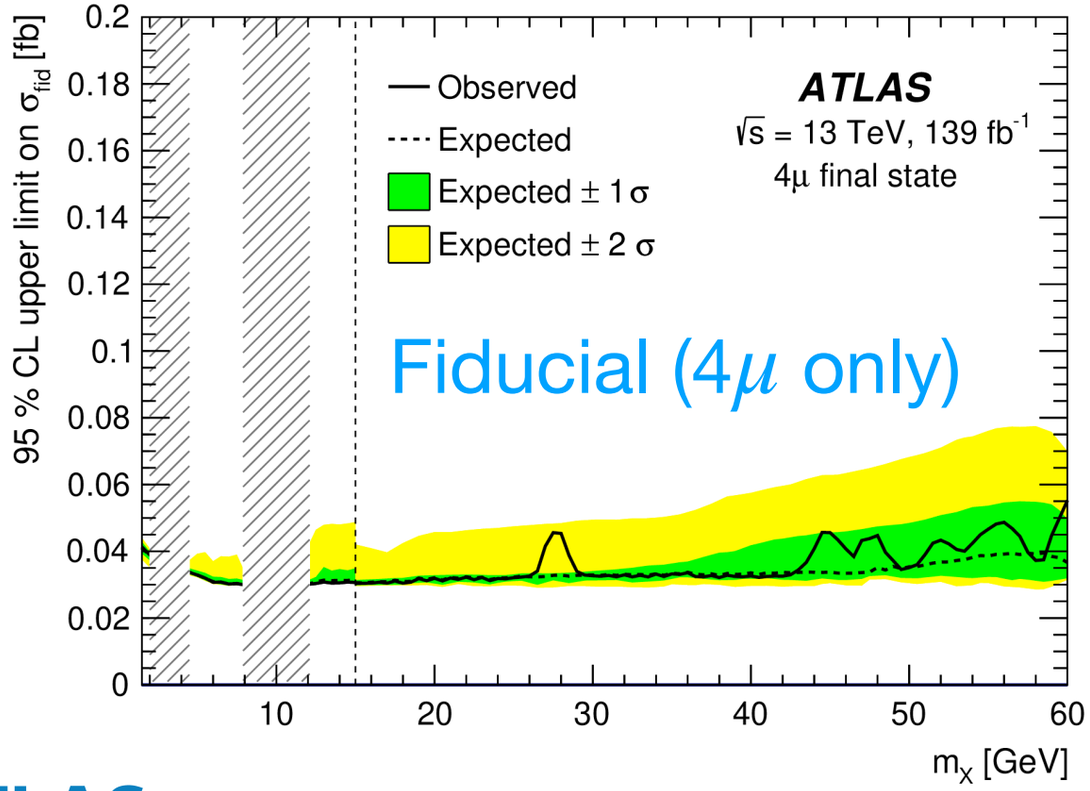
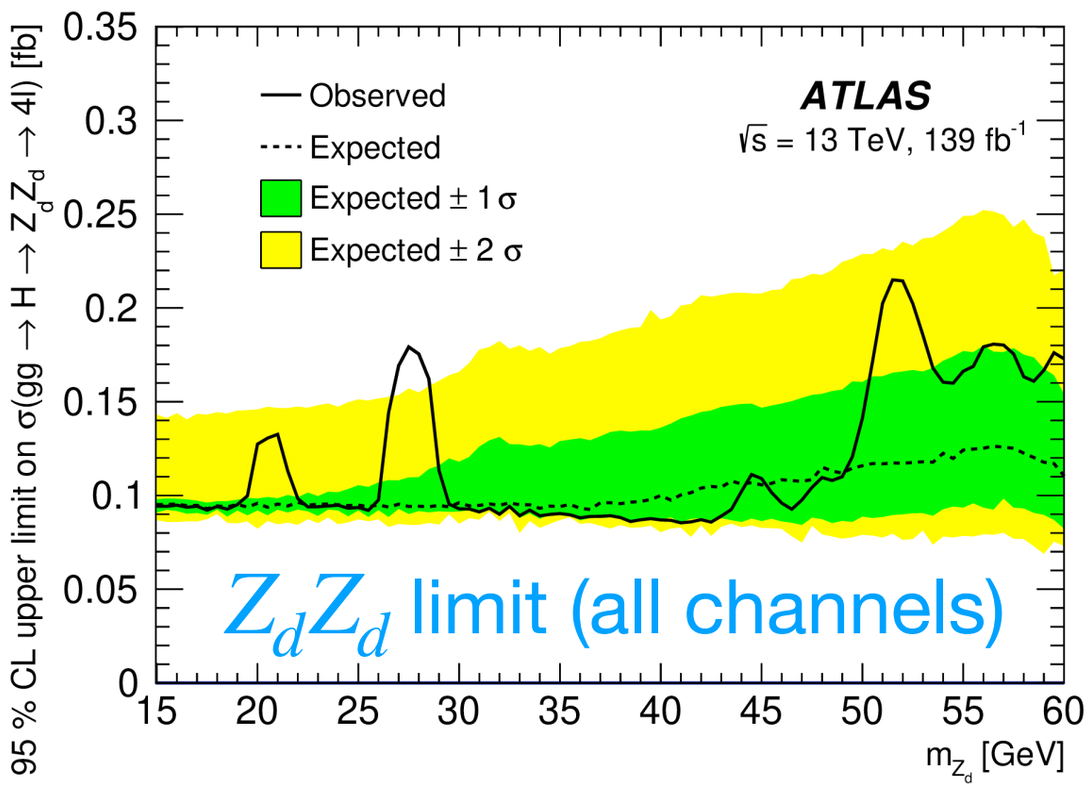
- No events observed in low mass signal region.
- Small excess seen around 28 GeV (local significance 2.5σ) in high-mass region.
- Improves limits by 2x-4x from increased luminosity and updated analysis selections







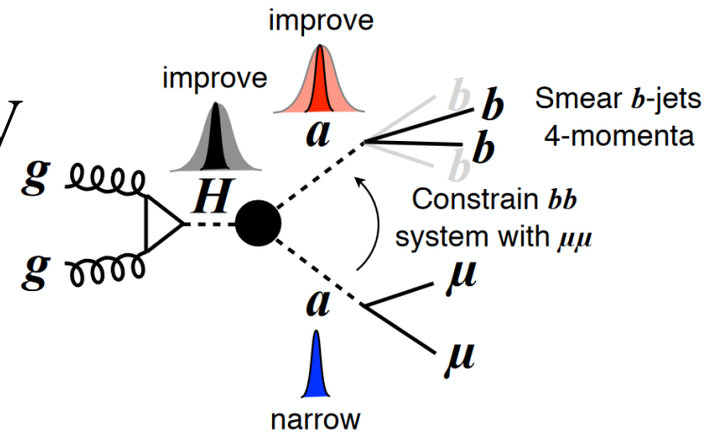
ATLAS EXPERIMENT

2110.13673, accepted by JHEP

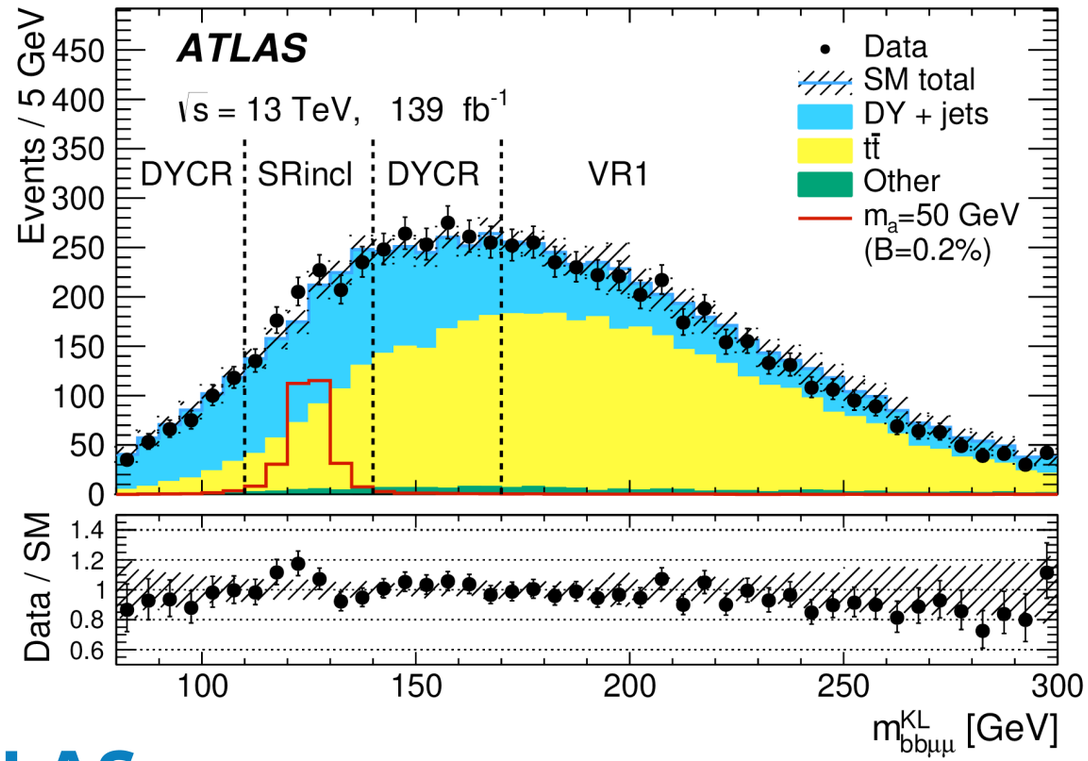
$H \to aa \to bb\mu\mu$

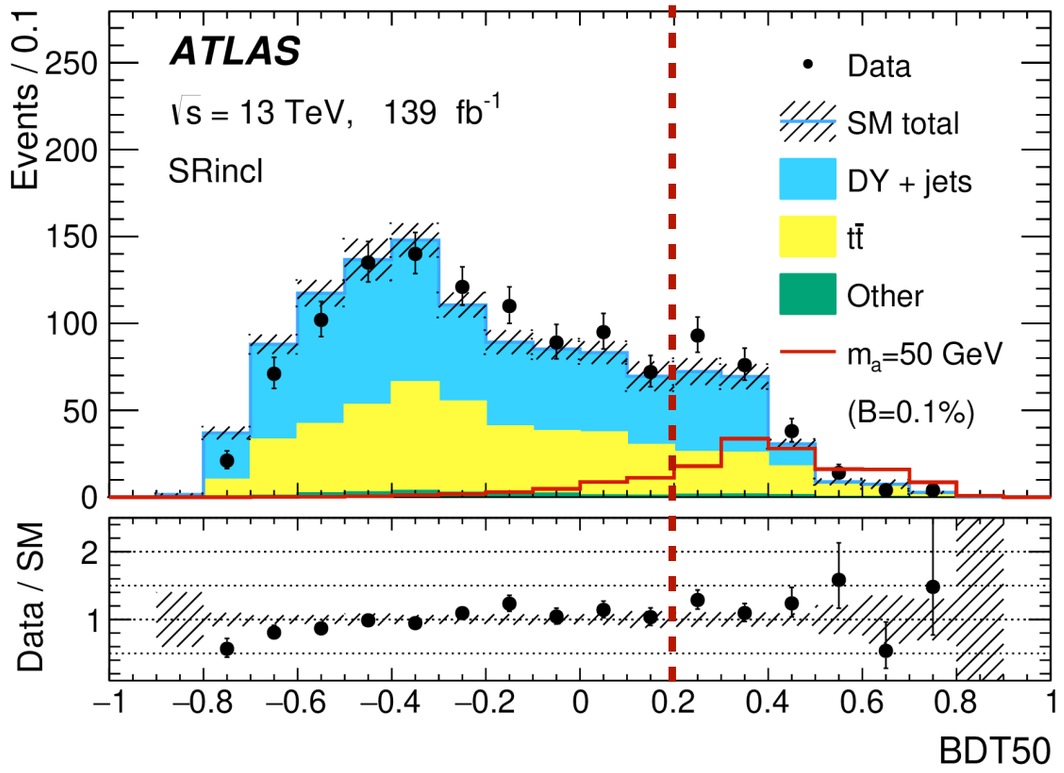
C. Hayes

- Targets exotic Higgs decays to pair of muons and b-jets using muon triggers, (large Br($a \to \mu\mu$) in lepton-specific models).
- Search performed in dimuon spectrum, $16 \leq m_{\mu\mu} < 62$ GeV
- Kinematic likelihood fit used to constrain $m_{bb} \approx m_{\mu\mu}$ and improves $m_{bb\mu\mu}$ resolution.



- Significant gains in sensitivity by using BDTs incorporating kinematic information. BDTs trained in partially overlapping 8 GeV wide windows in $m_{\mu\mu}$





ATLAS EXPERIMENT

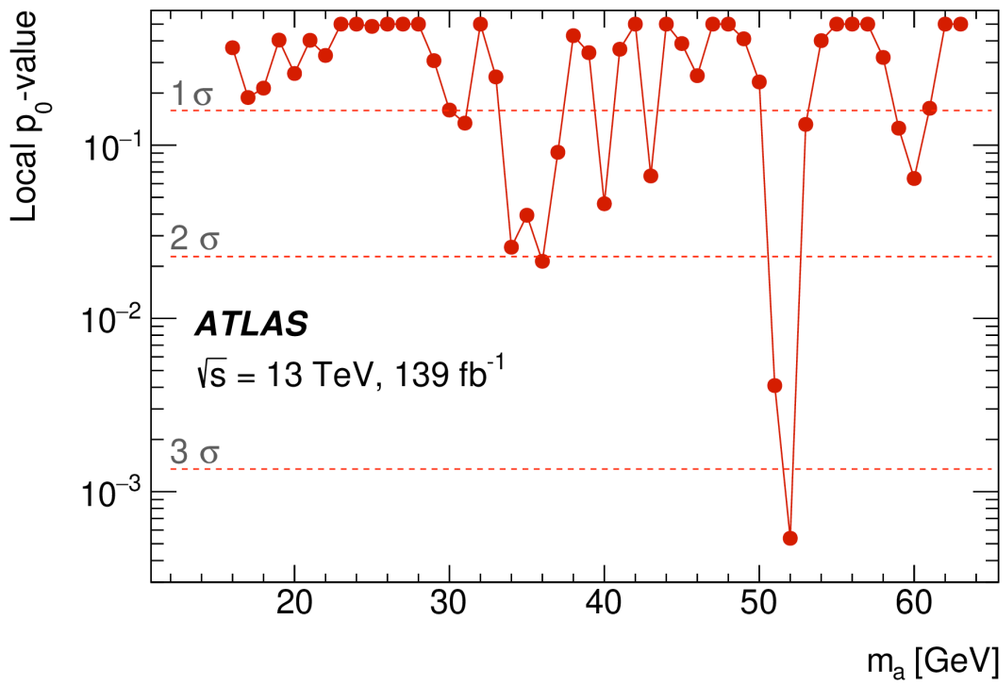
Phys. Rev. D 105 (2022) 012006

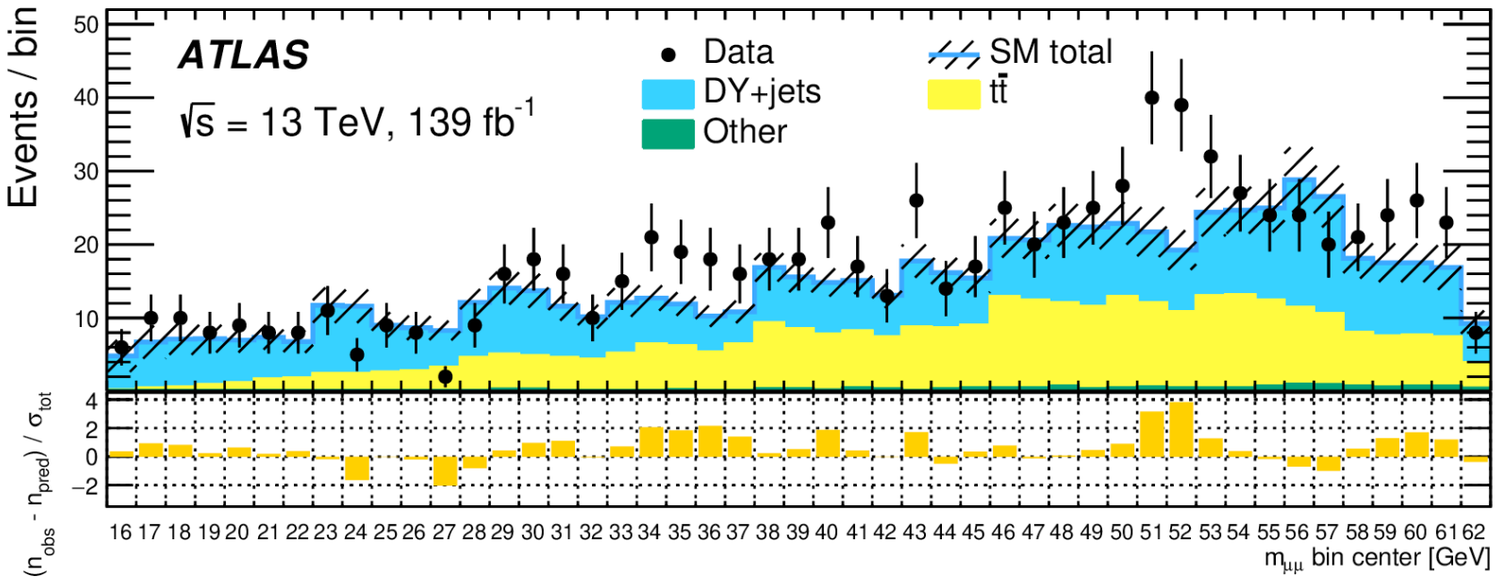
$H \to aa \to bb\mu\mu$

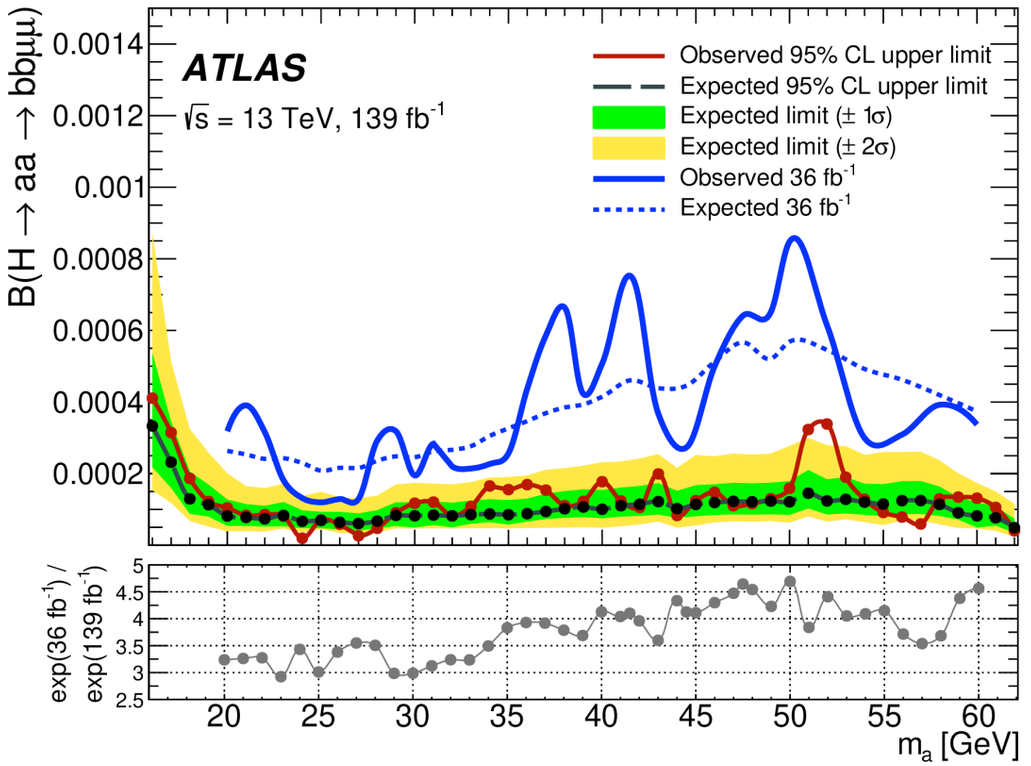
C. Hayes

- Fits performed in signal + control regions to test for the presence of an excess in $m_{\mu\mu}$ spectrum (2-3 GeV wide windows)
- Largest excess seen at $m_a = 52$ GeV, 3.3σ local / 1.7σ global.
- Limits set on Br($H \to aa \to bb\mu\mu$) between 0.2×10^{-4} - 4×10^{-4}, improving ATLAS limit by 2x-5x over previous result.

Phys. Rev. D 105 (2022) 012006







ATLAS EXPERIMENT

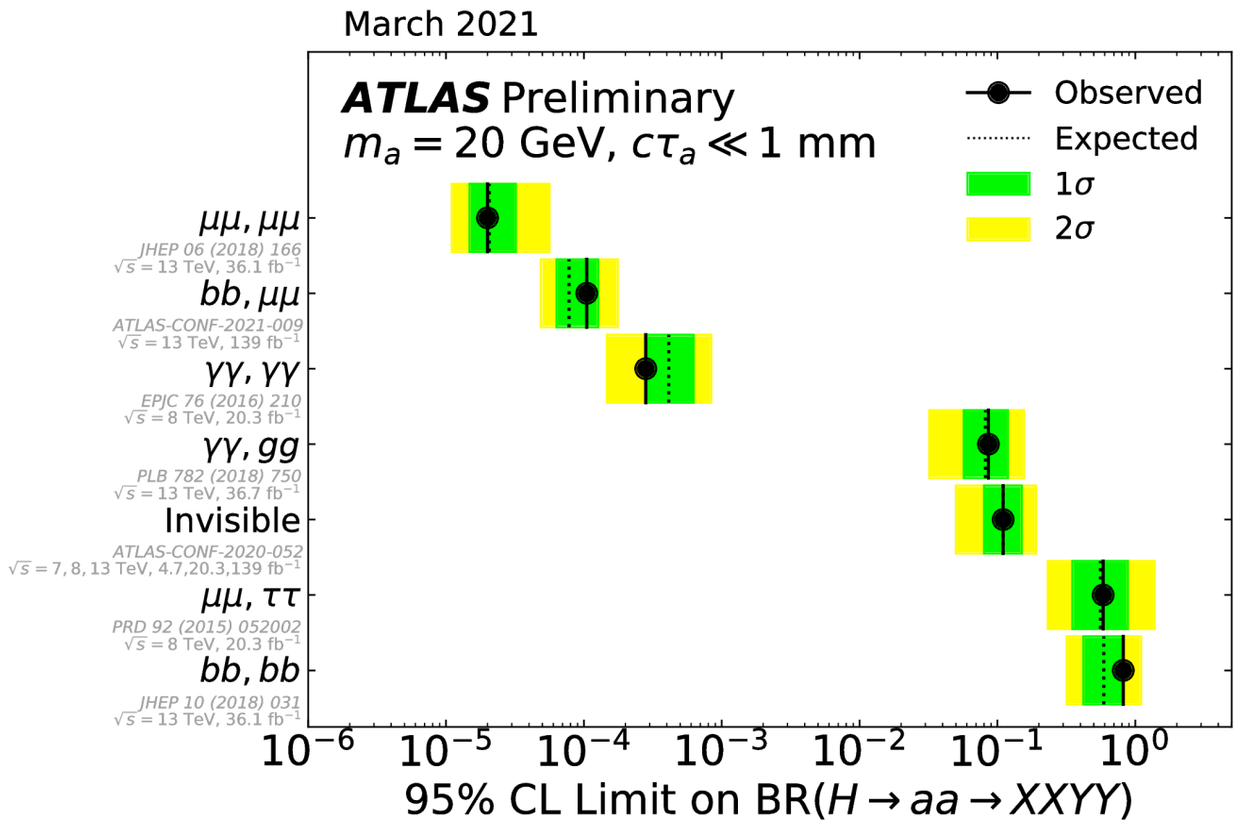
Note: overlapping bins!

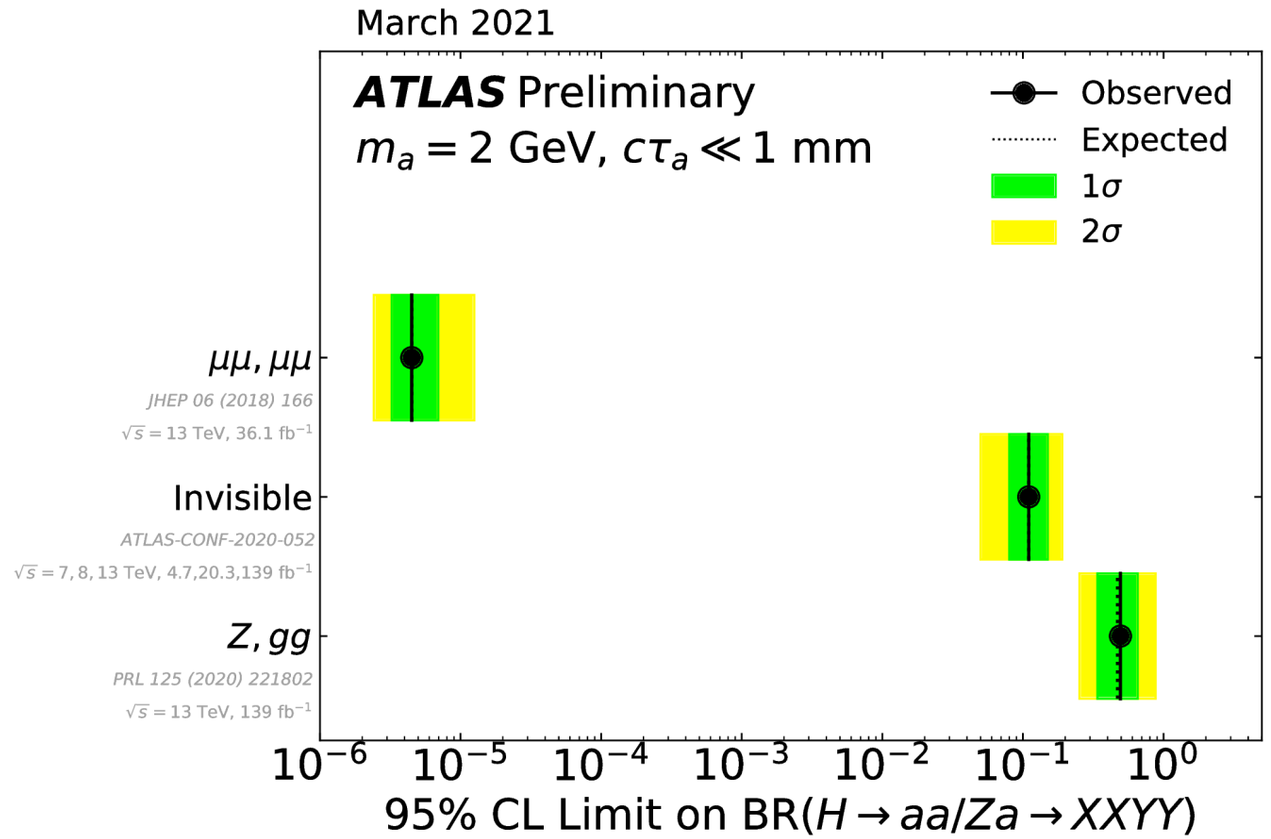
Run 2 Summary: Exotic Higgs Decays

C. Hayes

- Strong model-independent results are presented for searches for $H \to aa$ and $H \to Za$.

- Includes results current through Mar 2021 (results in 4μ now ~3x stronger).





ATL-PHYS-PUB-2021-008

Run 2 Summary: Exotic Higgs Decays

C. Hayes

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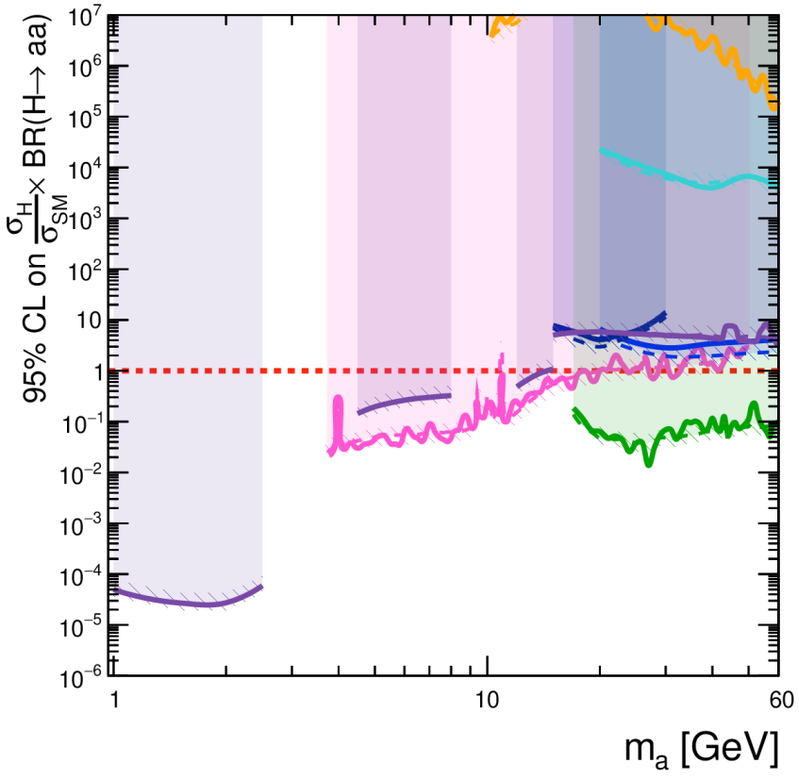
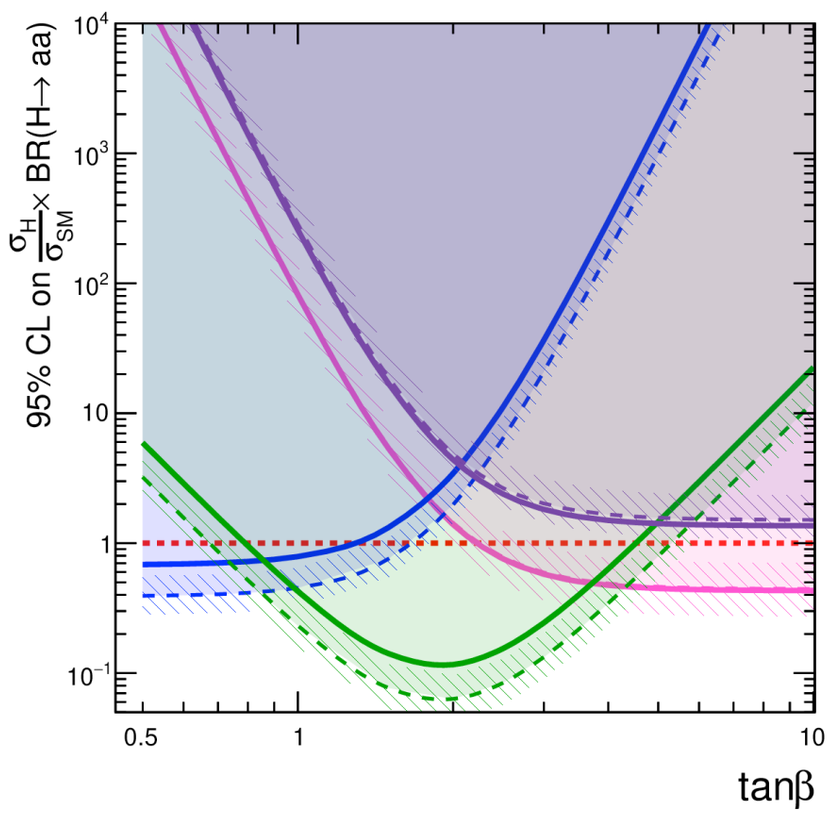
- Model independent limits on Br(H→2X 2Y) states are translated into limits on Br(H→aa) assuming a particular 2HDM+S model for couplings.
- Limits provided as a function of m_a for a fixed tan β and vice versa.
- Includes results current through Mar 2021 (results in 4μ now ~3x stronger).





$$\tan\beta = \nu_2/\nu_1$$

ATLAS EXPERIMENT

ATL-PHYS-PUB-2021-008

Searches for BSM Higgs at the LHC

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- After the discovery of the Higgs boson at 125 GeV: what is the nature of the Higgs sector? Is it completely SM or are new interactions waiting to be discovered?
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High-Mass

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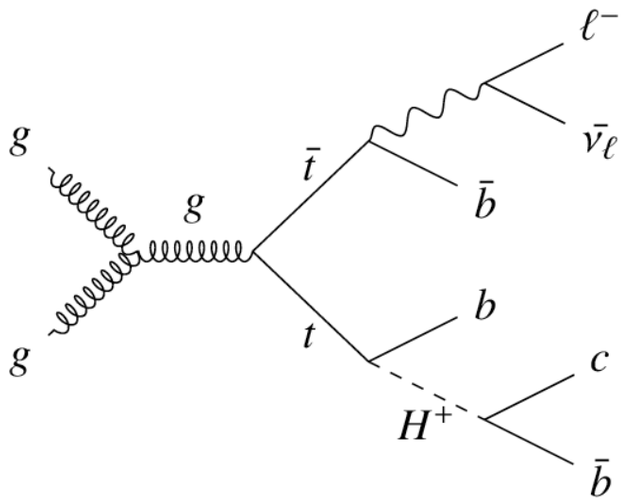
ATLAS EXPERIMENT

[1] ATLAS-CONF-2021-053

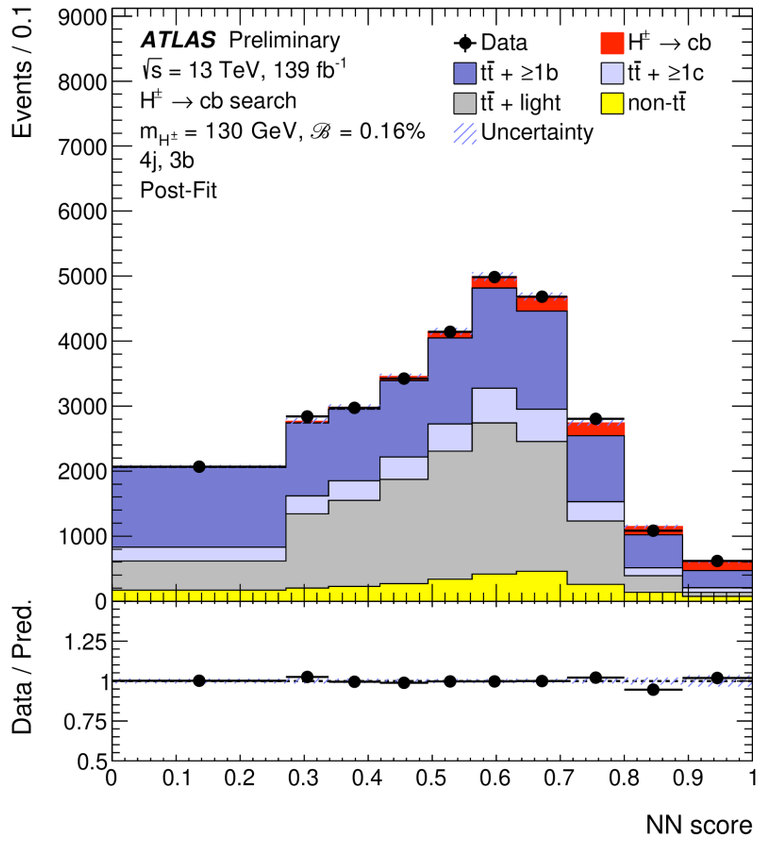
$H^{\pm} \to cb$

C. Hayes

- Interesting channel for 3HDM models at low $H^{\pm}$ mass.
- Search in events with an e/μ, high jet + b-jet multiplicity $\geq 4j,\ 3b$.
- Final discriminant based on a mass [parameterized neural network](#).
- Observed limits set on branching ratio Br($H^{\pm} \to cb$) as function of $m_{H^{\pm}}$ between 60 and 160 GeV.



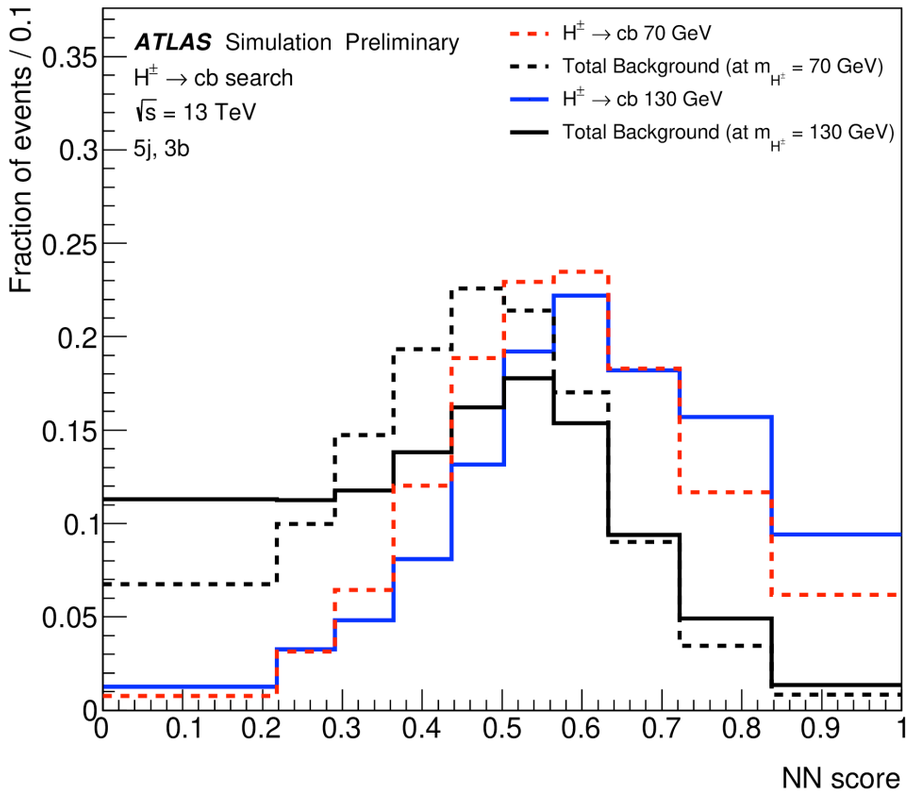
Improves on previous LHC result by 5x

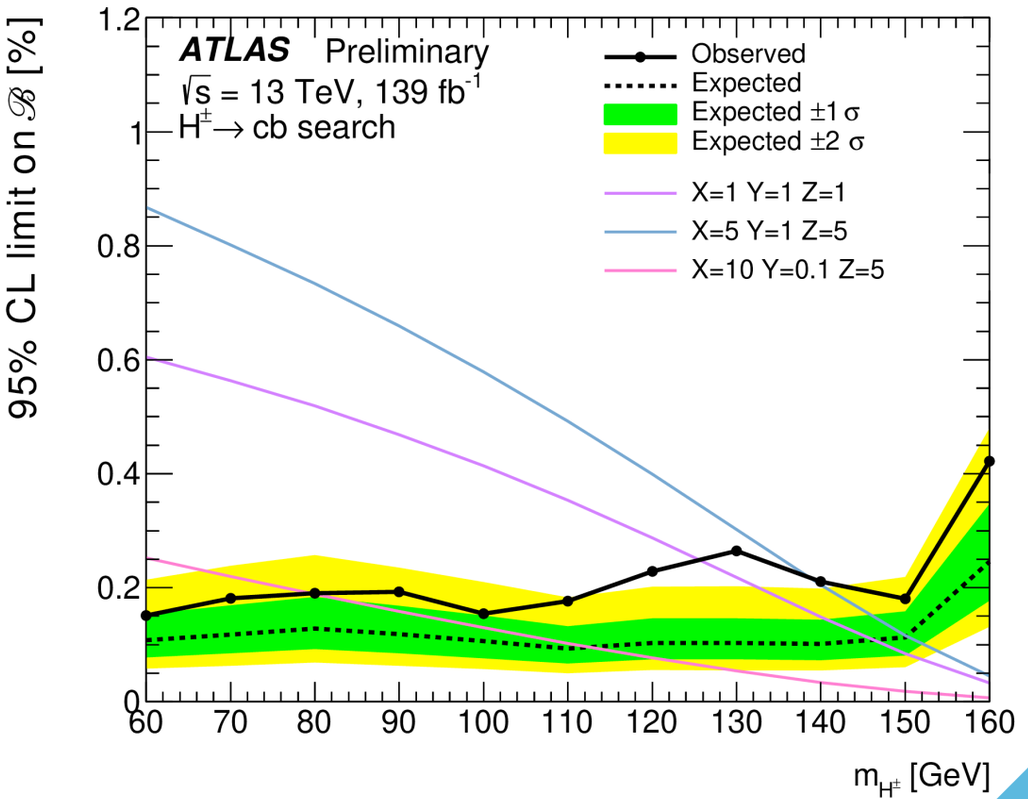


[ATLAS-CONF-2021-037](#)

Largest excess at $m_{H^{\pm}} = 130$ GeV

Local sig: $\approx 3\sigma$
global sig: 1.6σ





$H^{\pm} \to AW^{\pm}, A \to \mu\mu$

C. Hayes

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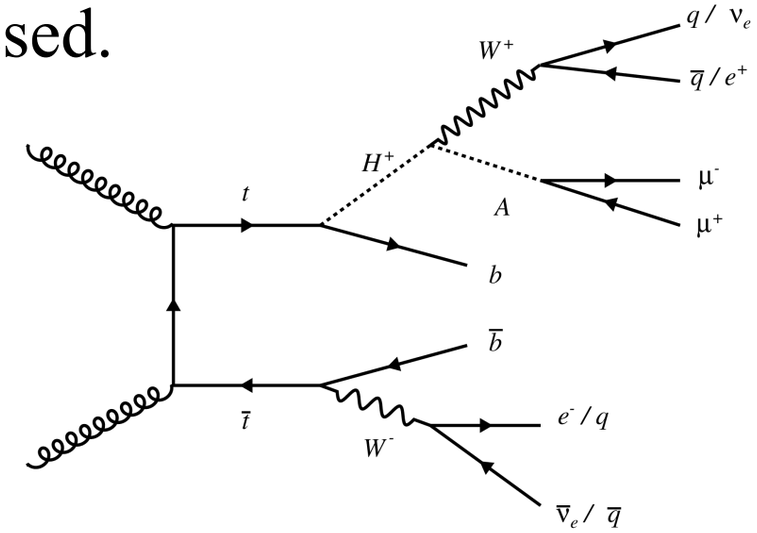
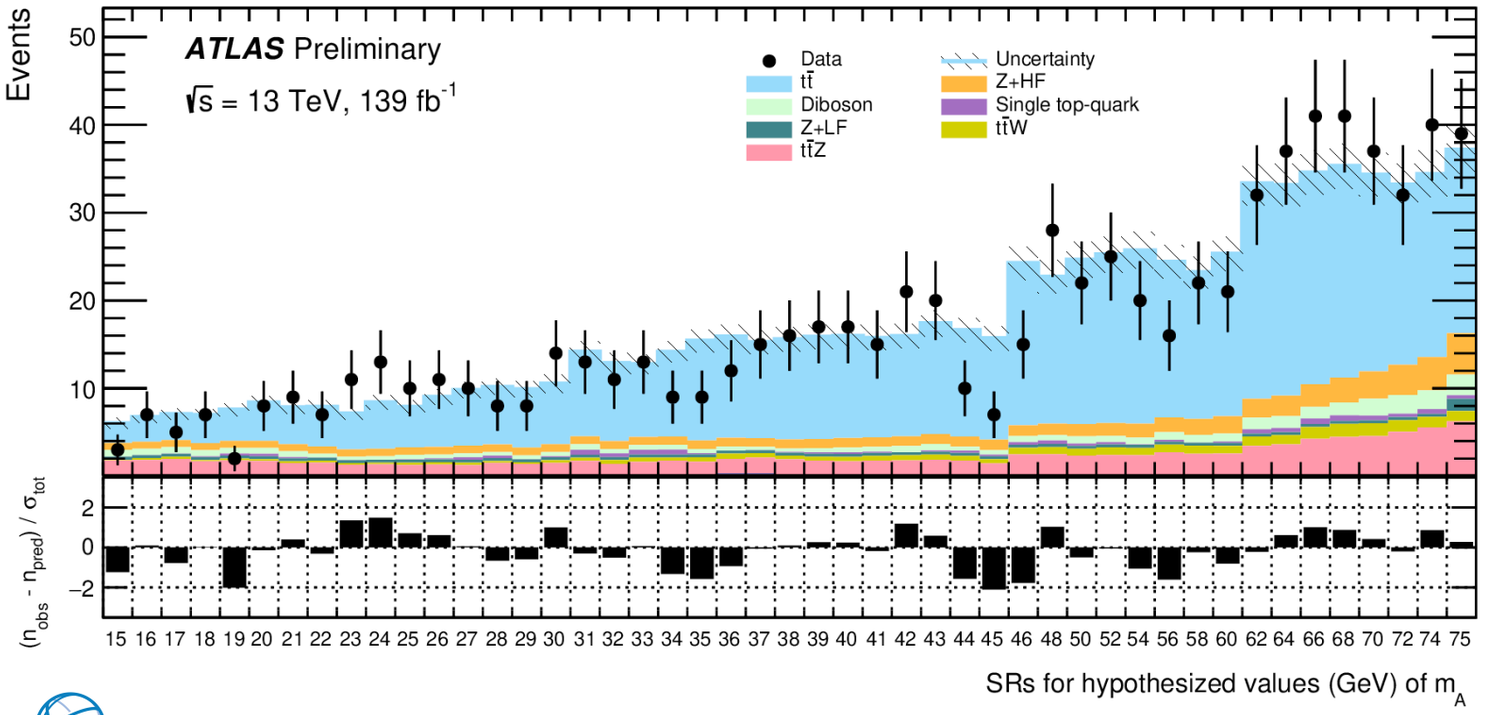
- In models where $H^{\pm} \to AW^{\pm}$ is kinematically allowed, branching ratios to fermionic states ($\tau\nu, cs$) can be suppressed.
- Search for low mass $H^{\pm}, A$ in $t\bar{t}$ decays in events with 1 electron, 2 muons, and 3 jets (1 b-jet)
- Search performed in $15 < m_{\mu\mu} < 75$ GeV region, count events in 1.5-4 GeV wide windows.



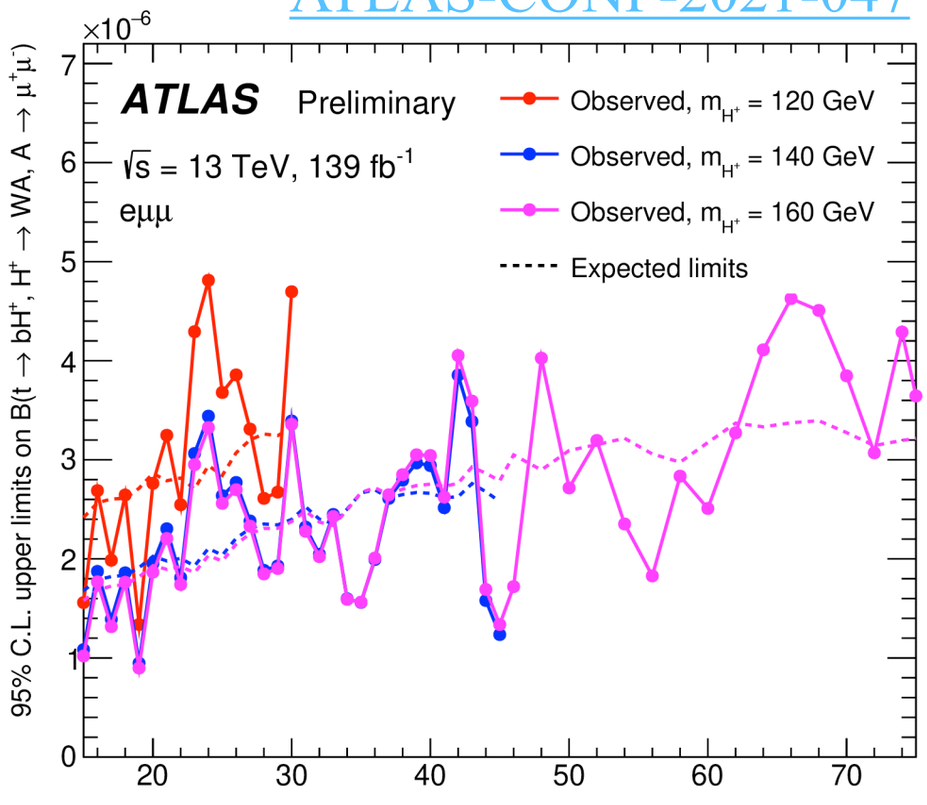
- No significant excess observed, limits set as a function of m_A for different $m_{H^{\pm}}$ hypotheses.



ATLAS EXPERIMENT

Note: overlapping bins!

ATLAS-CONF-2021-047



Competitive with CMS result

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High-Mass

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ATLAS EXPERIMENT

[1] ATLAS-CONF-2021-053

Heavy Neutral Higgs $H \to \gamma\gamma$

C. Hayes

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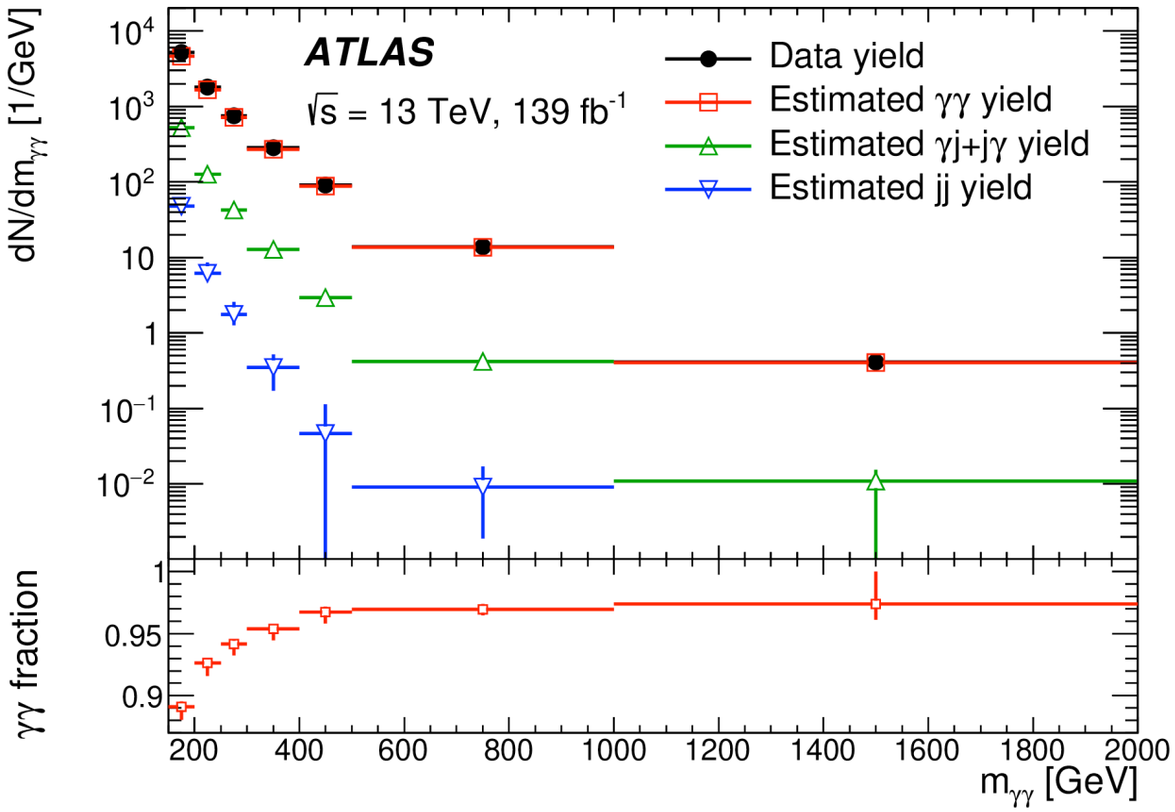
- Search for resonances in the high-mass ($m_{\gamma\gamma} > 150$ GeV) diphoton spectrum, benefitting from the excellent diphoton mass resolution.
- Requires 2 well-isolated photons with $E_T/m_{\gamma\gamma} > 0.3,\ 0.25$ for the leading and subleading photon respectively.

Phys. Lett. B 822 (2021) 136651



Signal: double-sided Crystal Ball fnc derived from MC + Breit-Wigner fcn to describe larger width signals.

Background function shape $x = m_{\gamma\gamma}/\sqrt{s}$

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

derived from MC template of $\gamma\gamma$ events + data-driven estimates of $yj + jj$ events

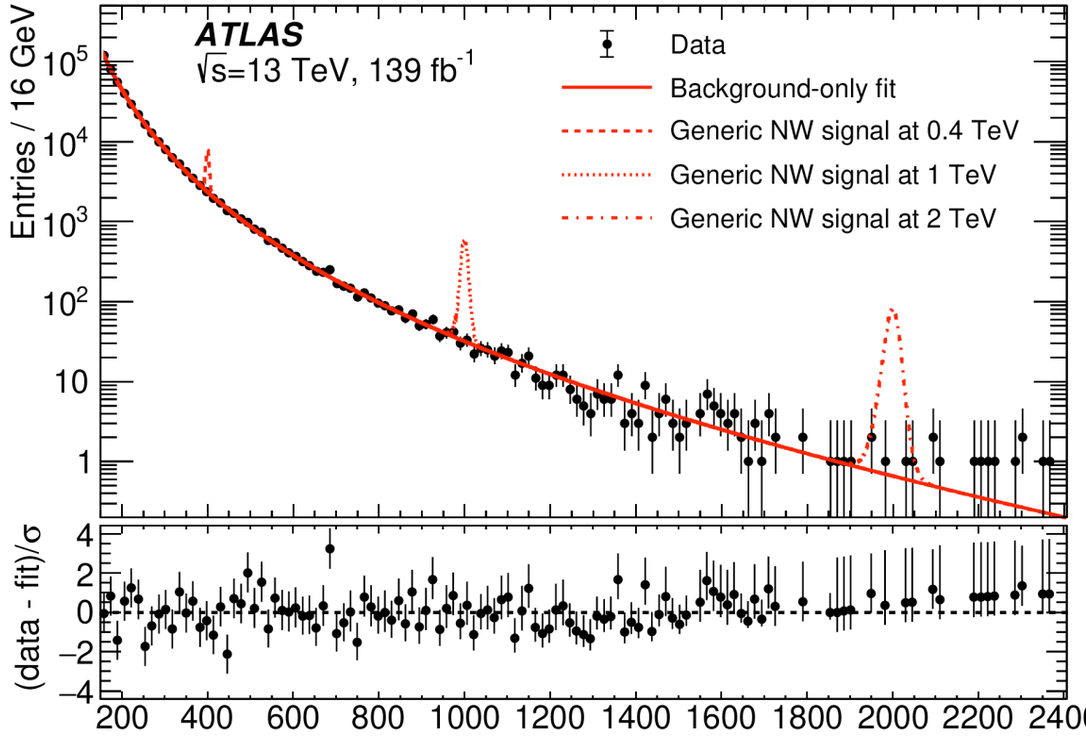
$\gamma\gamma$ purity estimated in data ~89-97%

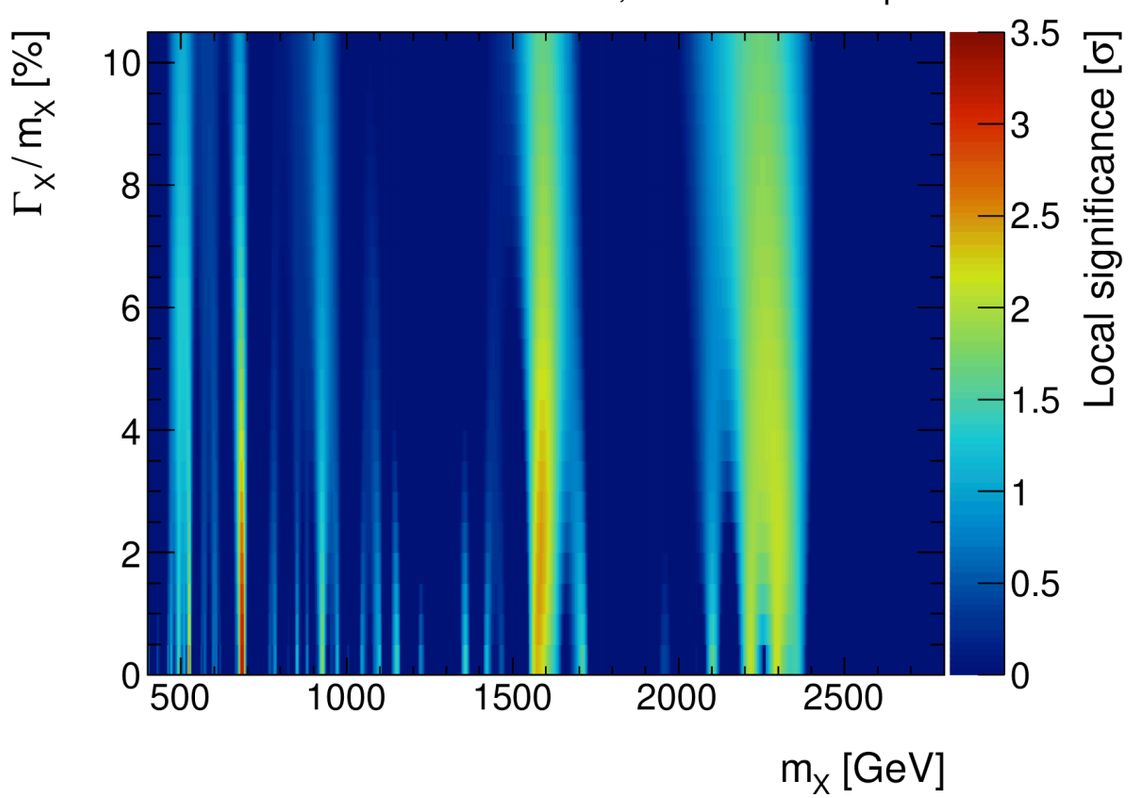
Heavy Neutral Higgs $H \to \gamma\gamma$

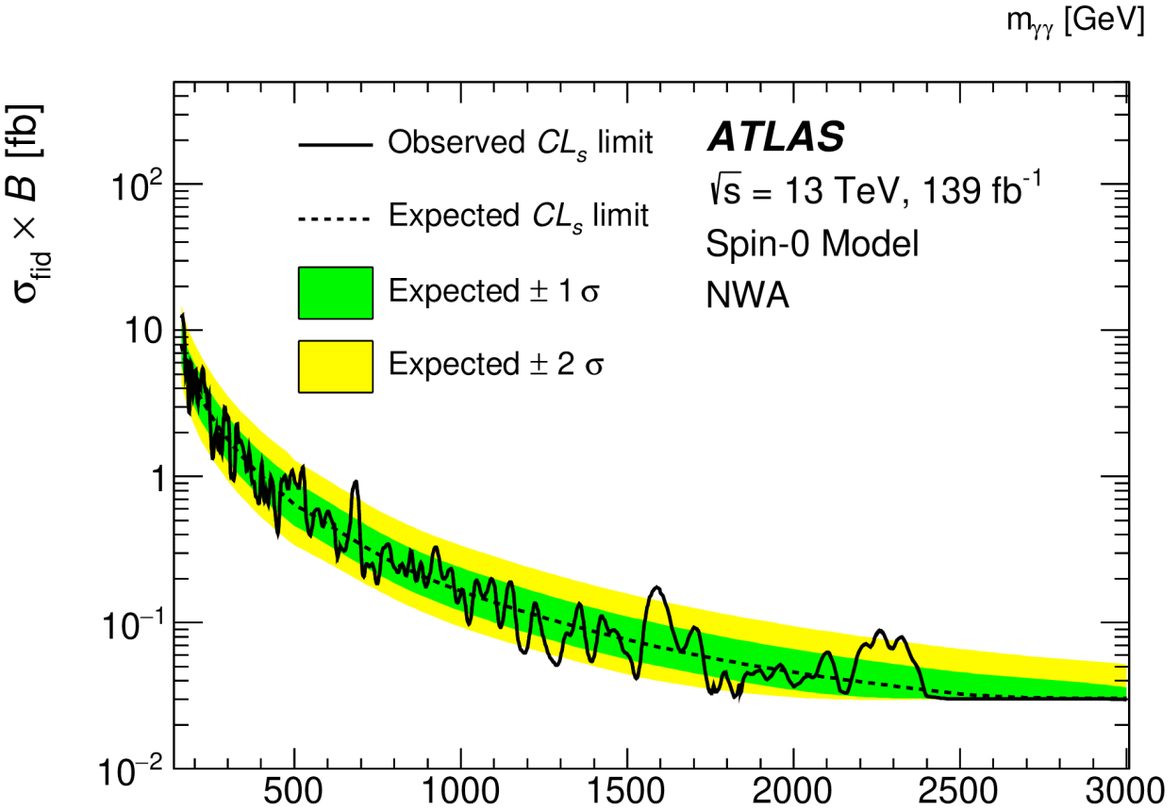
C. Hayes

- No significant excess observed. Largest deviation at $m_X = 684$ GeV for narrow-width signals with 3.3σ local / 1.3σ global significance.

- Limits set on fiducial cross-section as a function of m_X for widths $\Gamma_X/m_X = [0,10]\,\%$







Phys. Lett. B 822 (2021) 136651

Summary

C. Hayes

- Several new searches by the ATLAS experiment targeting new scalar resonances have been presented, including the production of new light resonances in the decays of the 125 GeV Higgs Boson, charged Higgs in $t\bar{t}$ decays, and searches for heavy resonances.

- No significant deviations from the SM have been observed, but each search provides sensitive probes of new physics in the Higgs sector.

- Many analyses beyond the ones shown here!
  - A selection of diboson resonance searches: ATL-PHYS-PUB-2021-018 (talk by Fang-Ying from Monday!)
  - Summary of Higgs to light resonance searches: ATL-PHYS-PUB-2021-008
  - Long-lived signatures (talk by Jyoti from Monday!)

- Many new exciting results and possibilities to come for the full Run-2 (and future Run-3) datasets!

Backup

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2HDM+S Models

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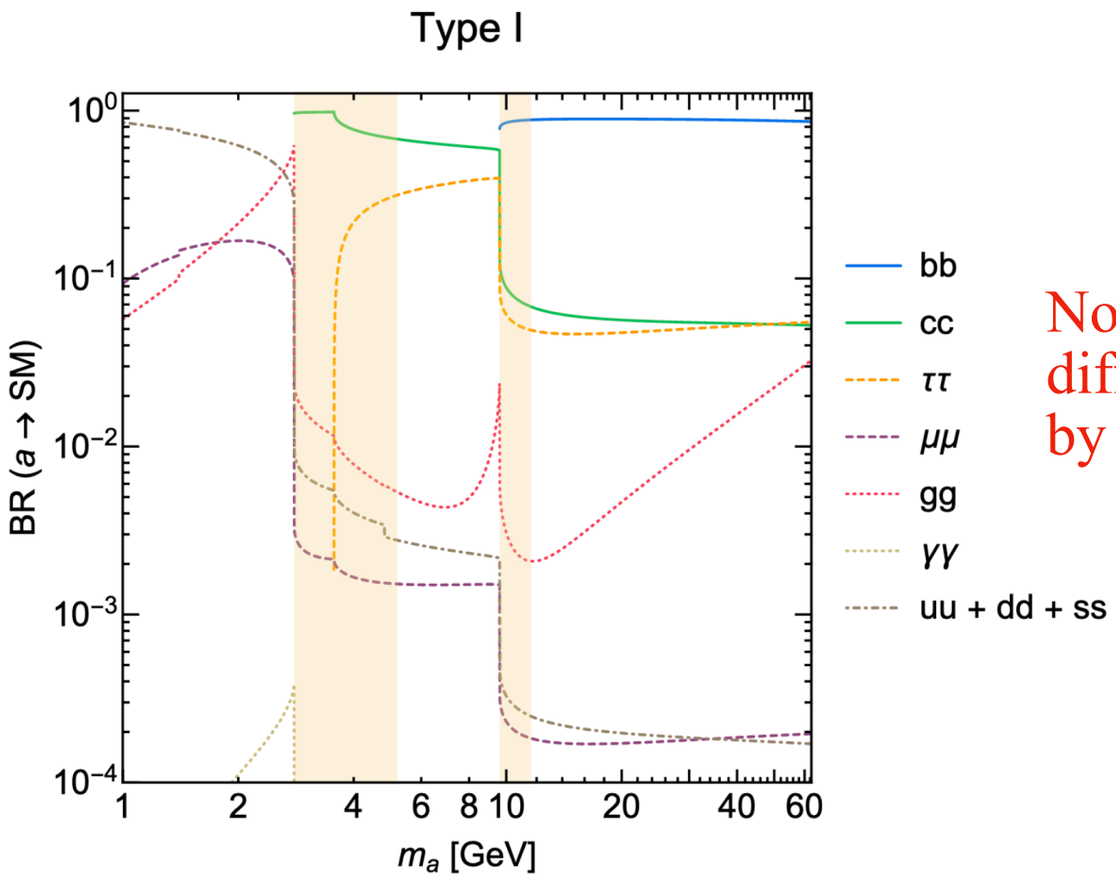
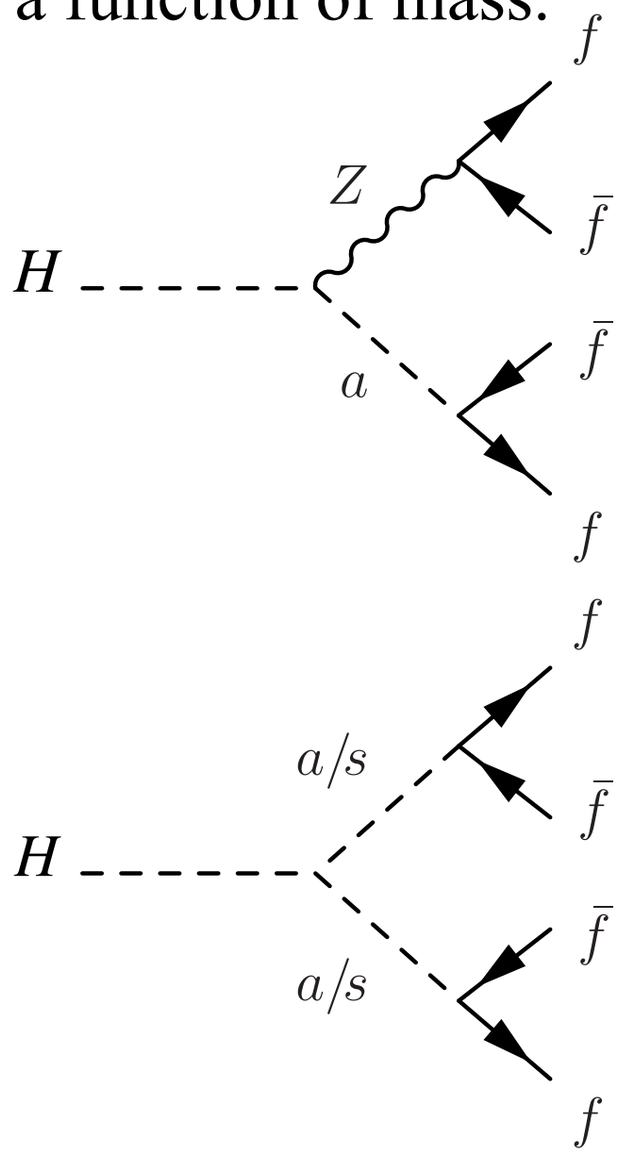
- One interesting extension of the SM includes a second Higgs doublet and an additional singlet. This 2HDM+S model predicts exotic Higgs decays via new (pseudo)scalar states.
- New decays to 4-body final states can come from ss, aa, or Za interactions.
- Decay to SM particles determined via Yukawa interactions. Many different channels to search and dominant decay modes change as a function of mass.



Note: Can enhance different couplings by changing 2HDM!



D. Curtin, et al.
Phys. Rev. D 90 , 075004

$H^{\pm} \to cb$

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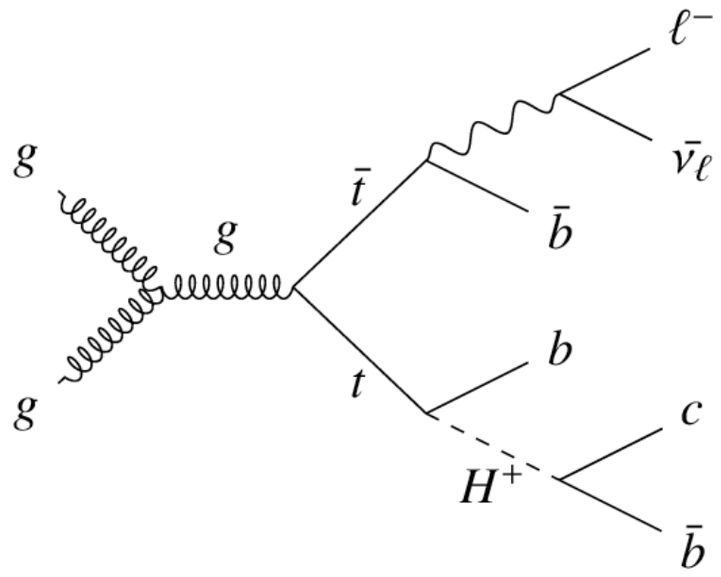
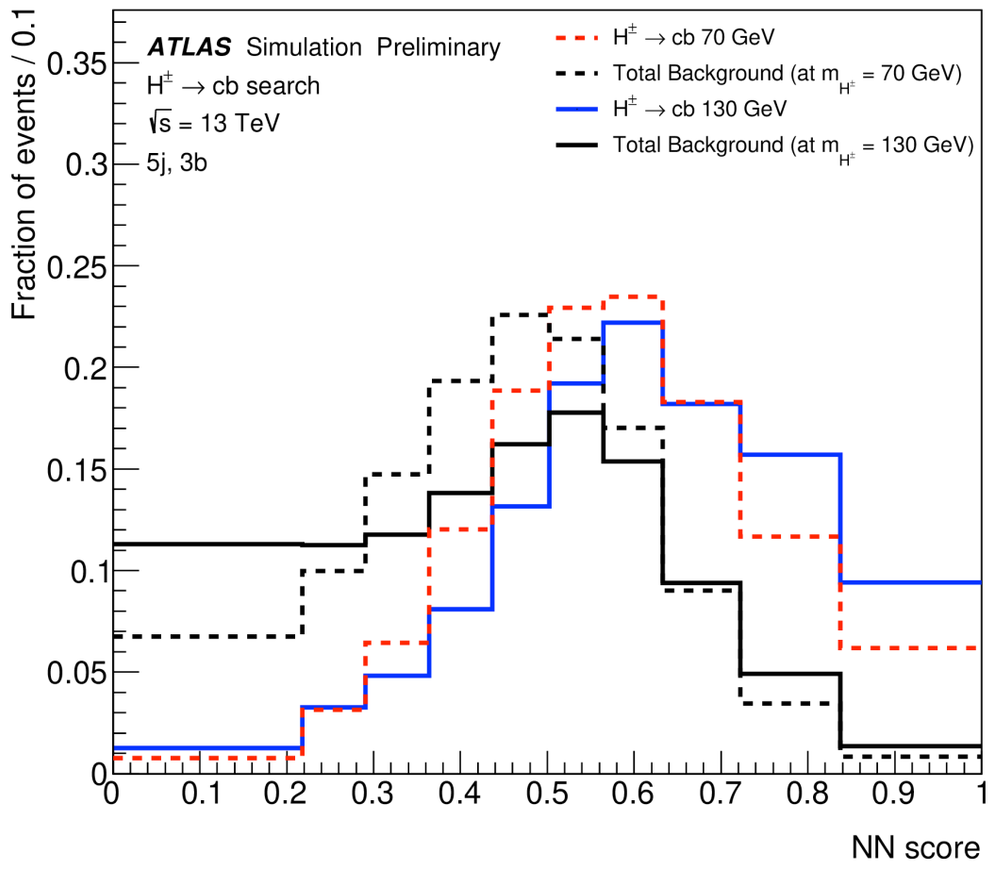
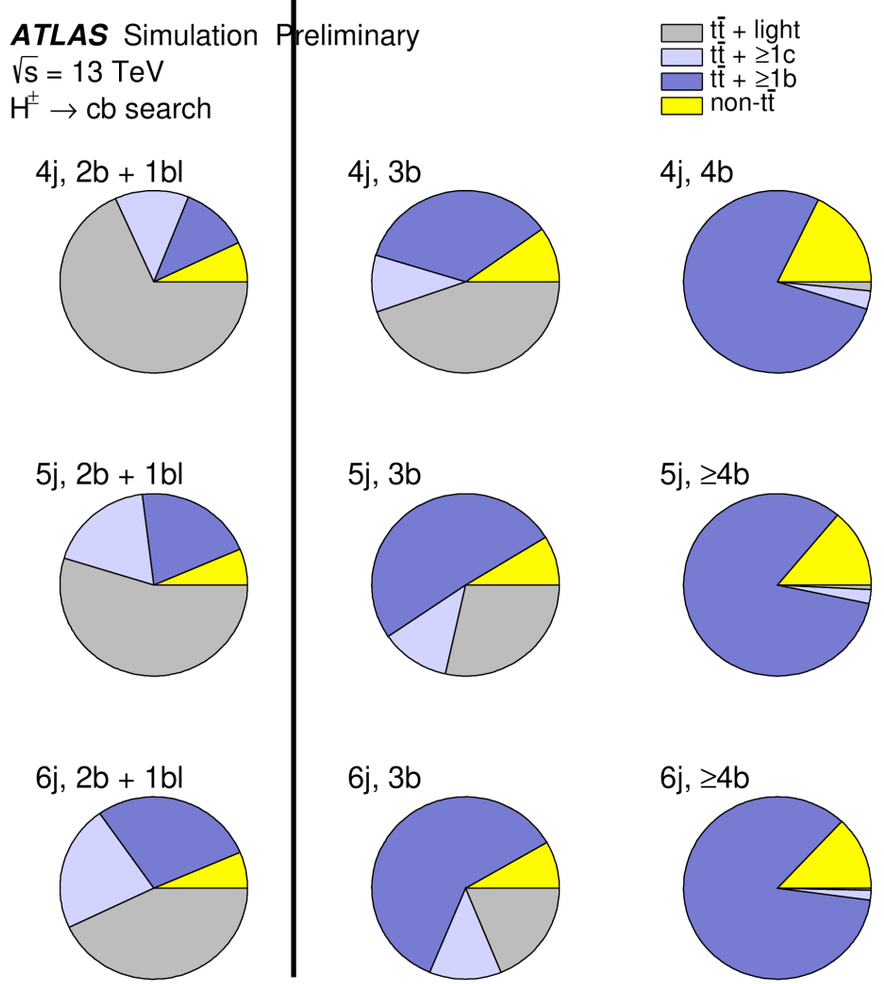
- Search performed in events with 1 e/μ used for triggering and high-jet + b-jet multiplicity $\geq 4j$, $3b$. Events are further categorized based on the number of jets and b-jets.

- Final discriminant from a feed-forward mass parameterized neural network based on low-level kinematic, b-tagging, and invariant masses of jet pairs.



Fit regions (CRs + SRs)





$H^{\pm} \rightarrow cb$

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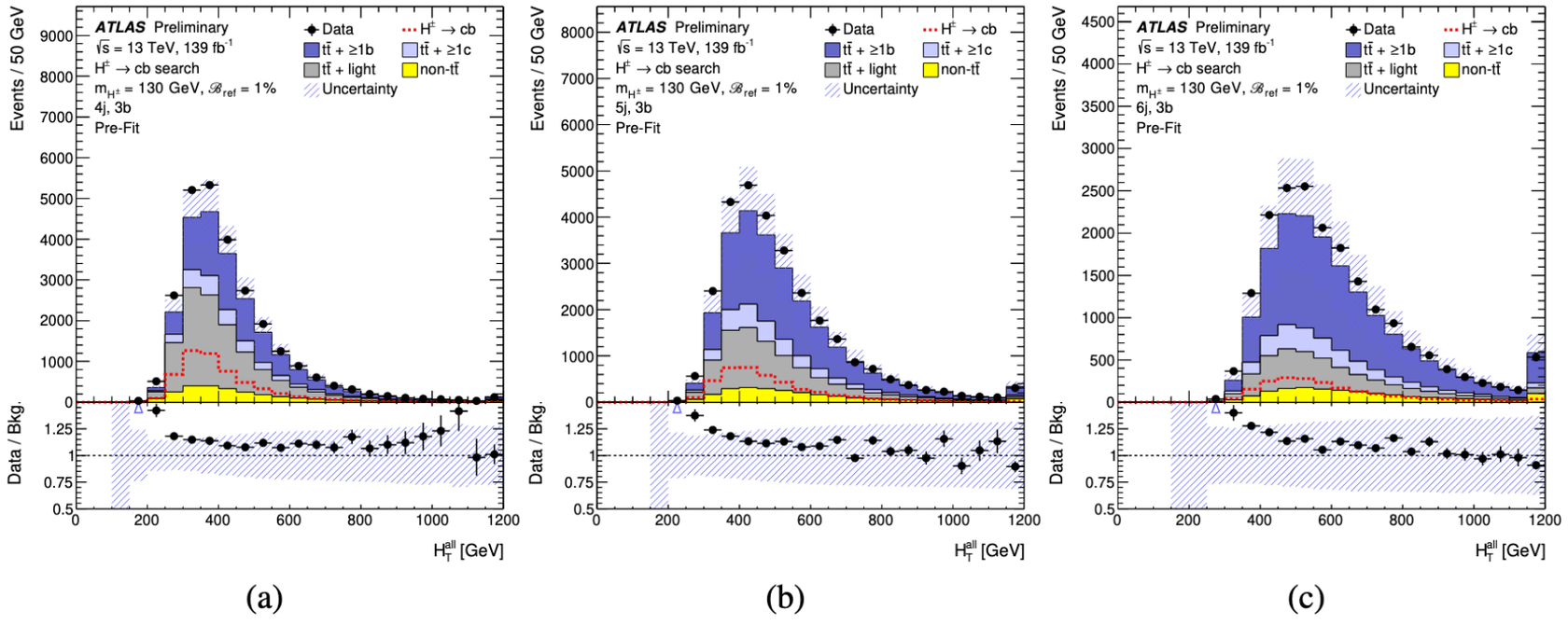
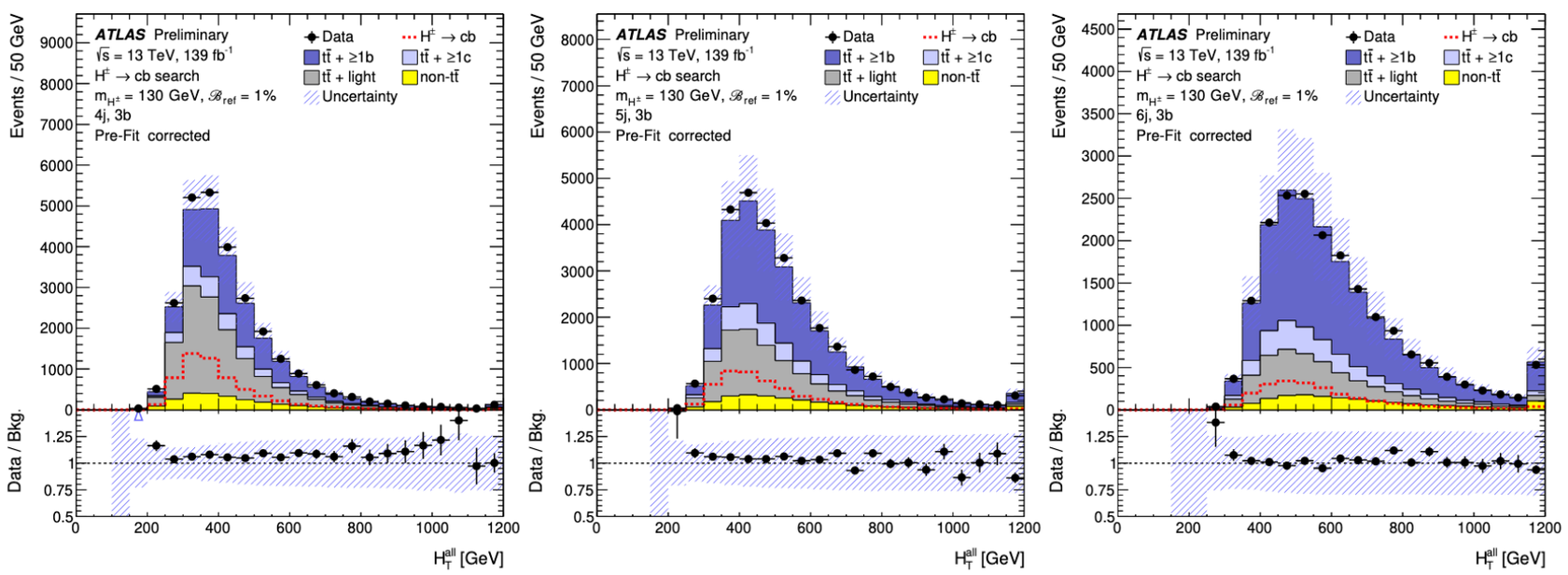
Corrections to $t\bar{t}$ background using H_T based reweighting in bins of jet multiplicity in dedicated loose b-tagging control region.

Correction factor close to one for high H_T (> 800 GeV)





$$C(H_{\mathrm{T}}^{\mathrm{all,\,i}},\ \mathrm{j}^{i}) = \frac{N^{\mathrm{data}}(H_{\mathrm{T}}^{\mathrm{all,\,i}},\ \mathrm{j}^{i}) - N^{\mathrm{non\text{-}}t\bar{t}}(H_{\mathrm{T}}^{\mathrm{all,\,i}},\ \mathrm{j}^{i})}{N^{t\bar{t}}(H_{\mathrm{T}}^{\mathrm{all,\,i}},\ \mathrm{j}^{i})}$$

$H^{\pm} \to cb$ Pre-fit vs Post-fit

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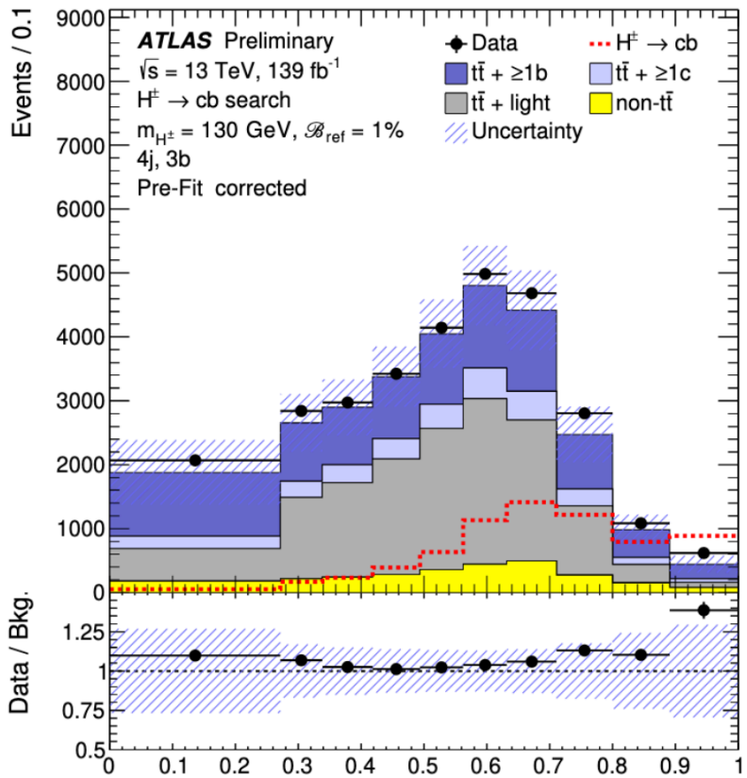
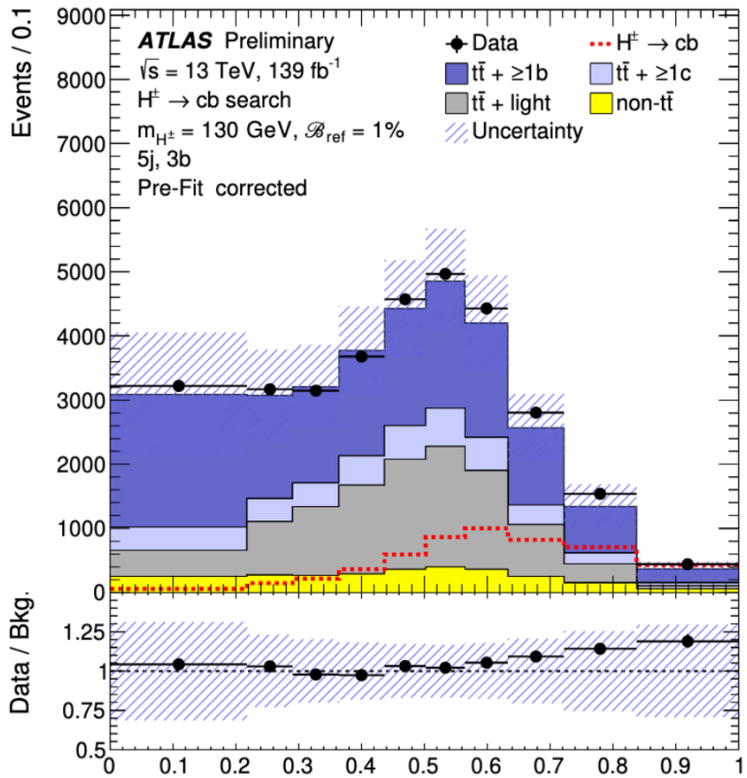
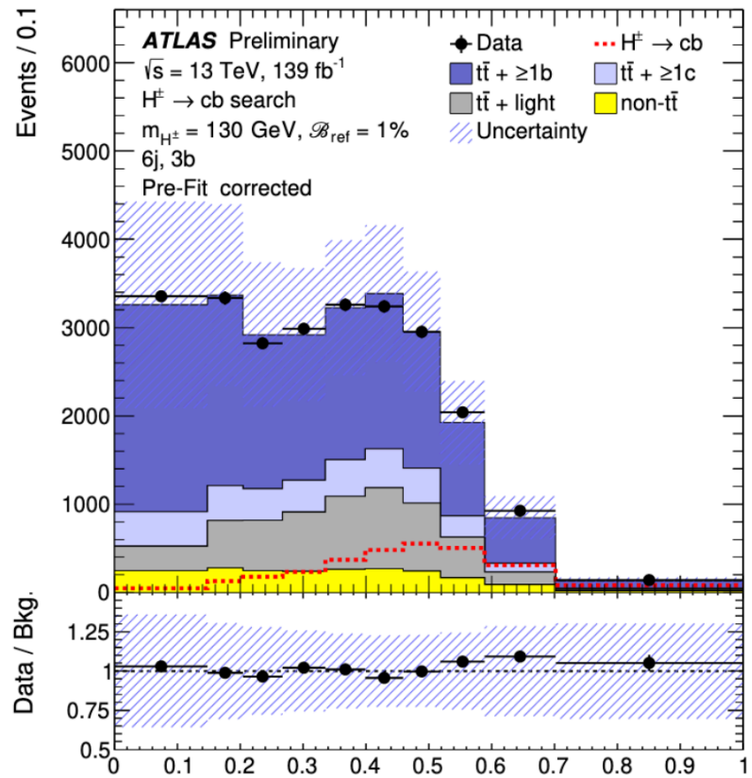
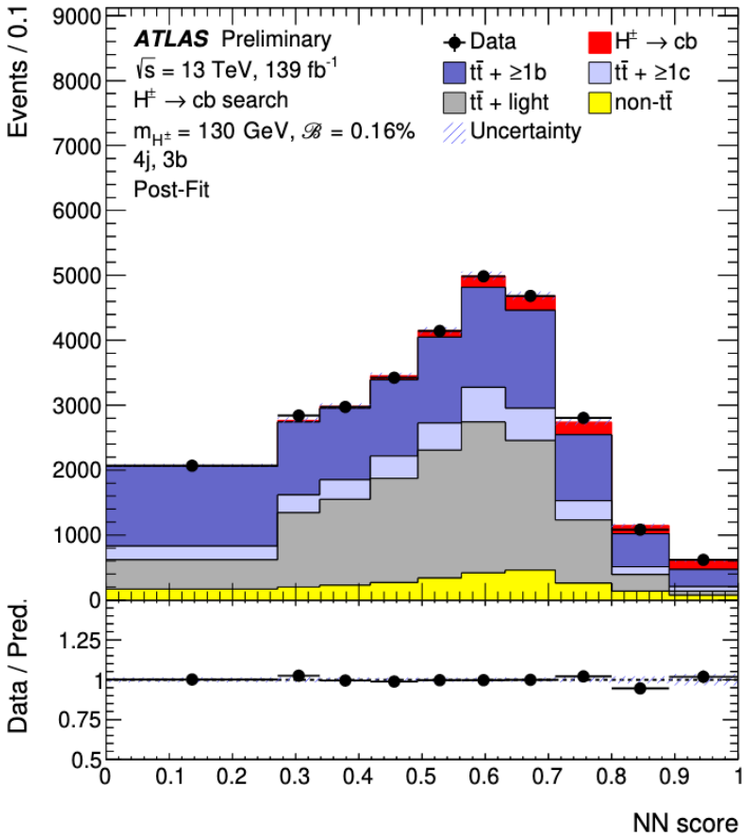
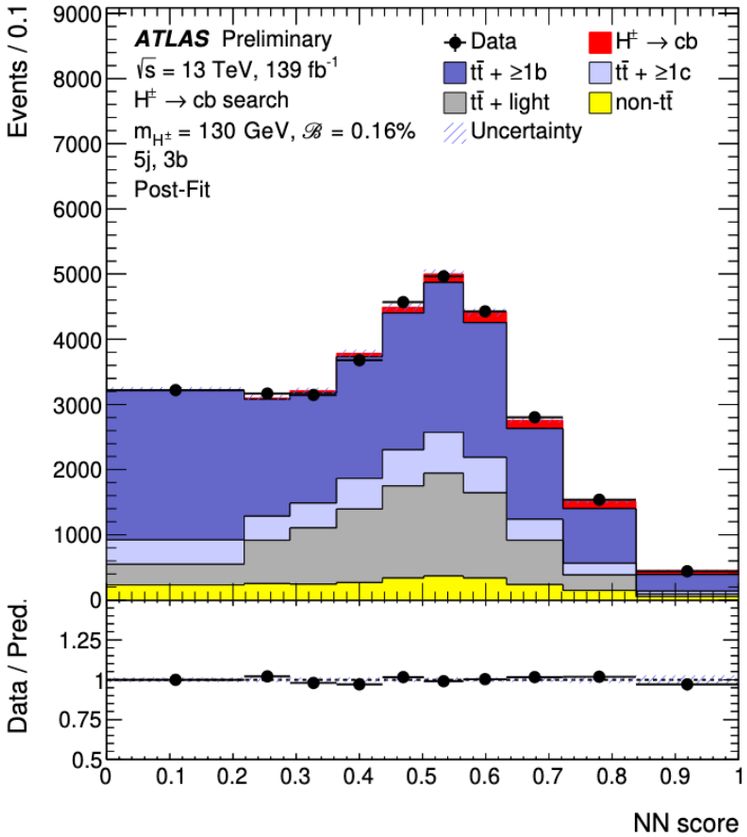


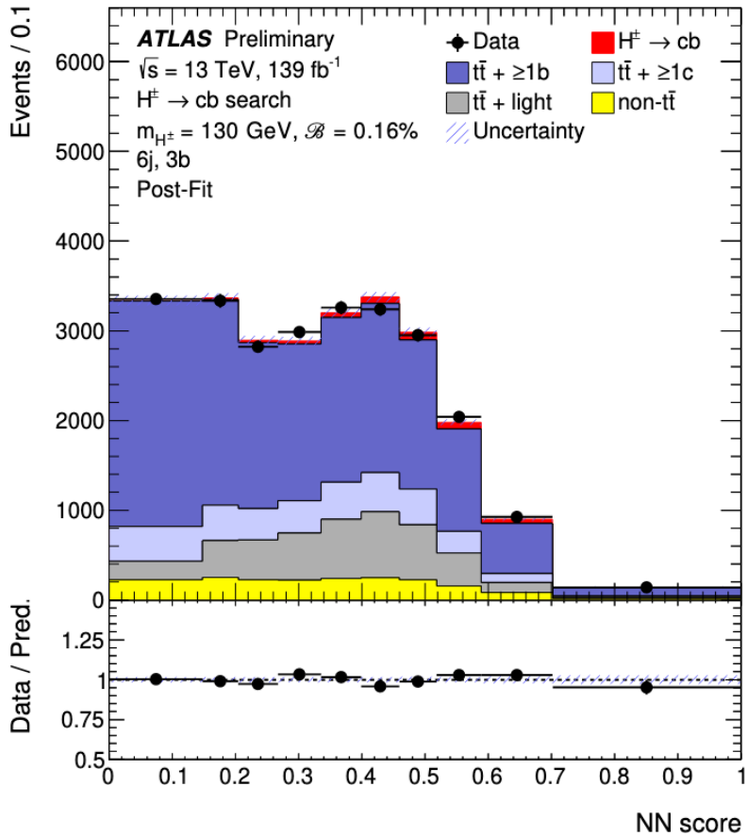




NN score



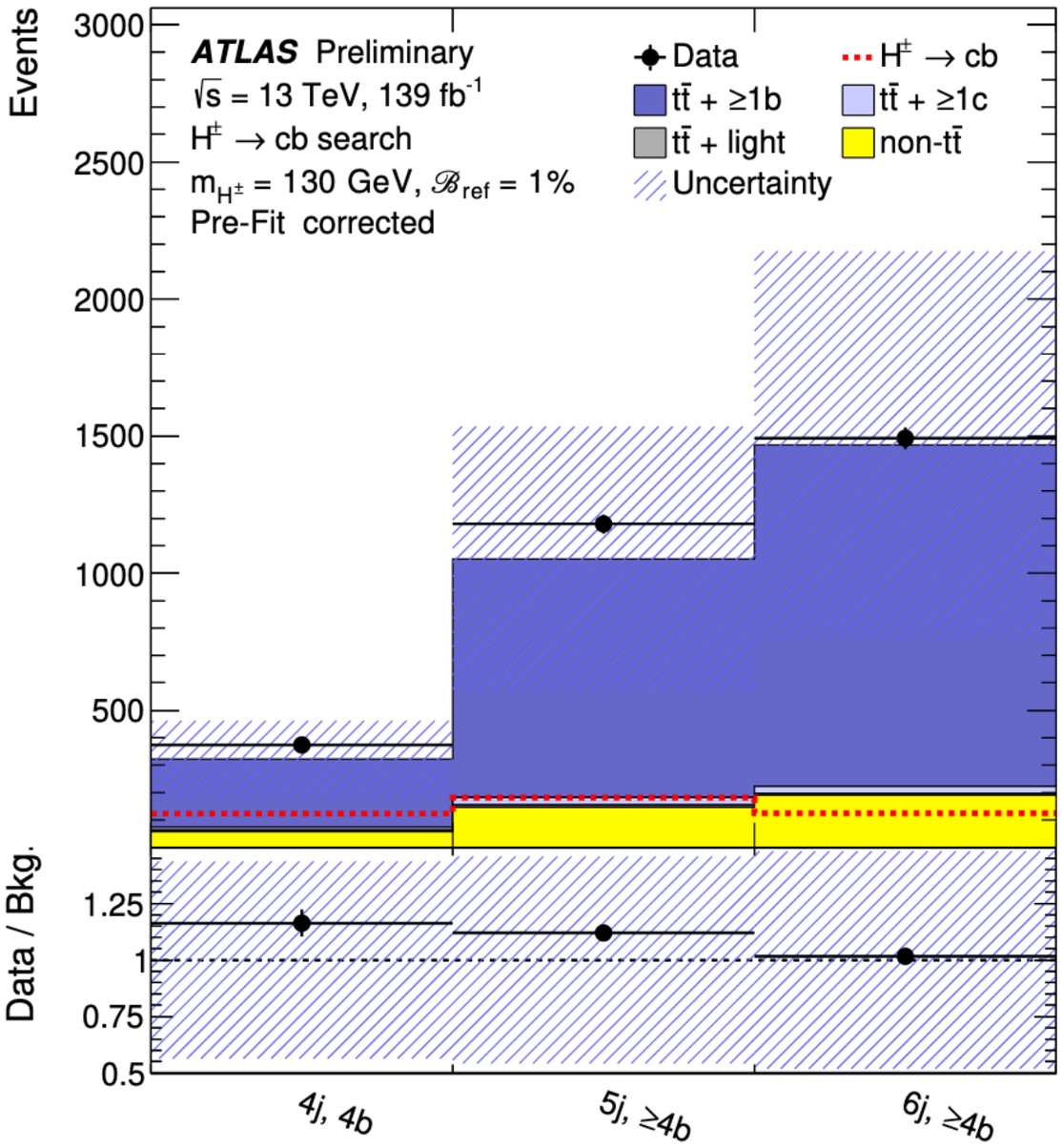


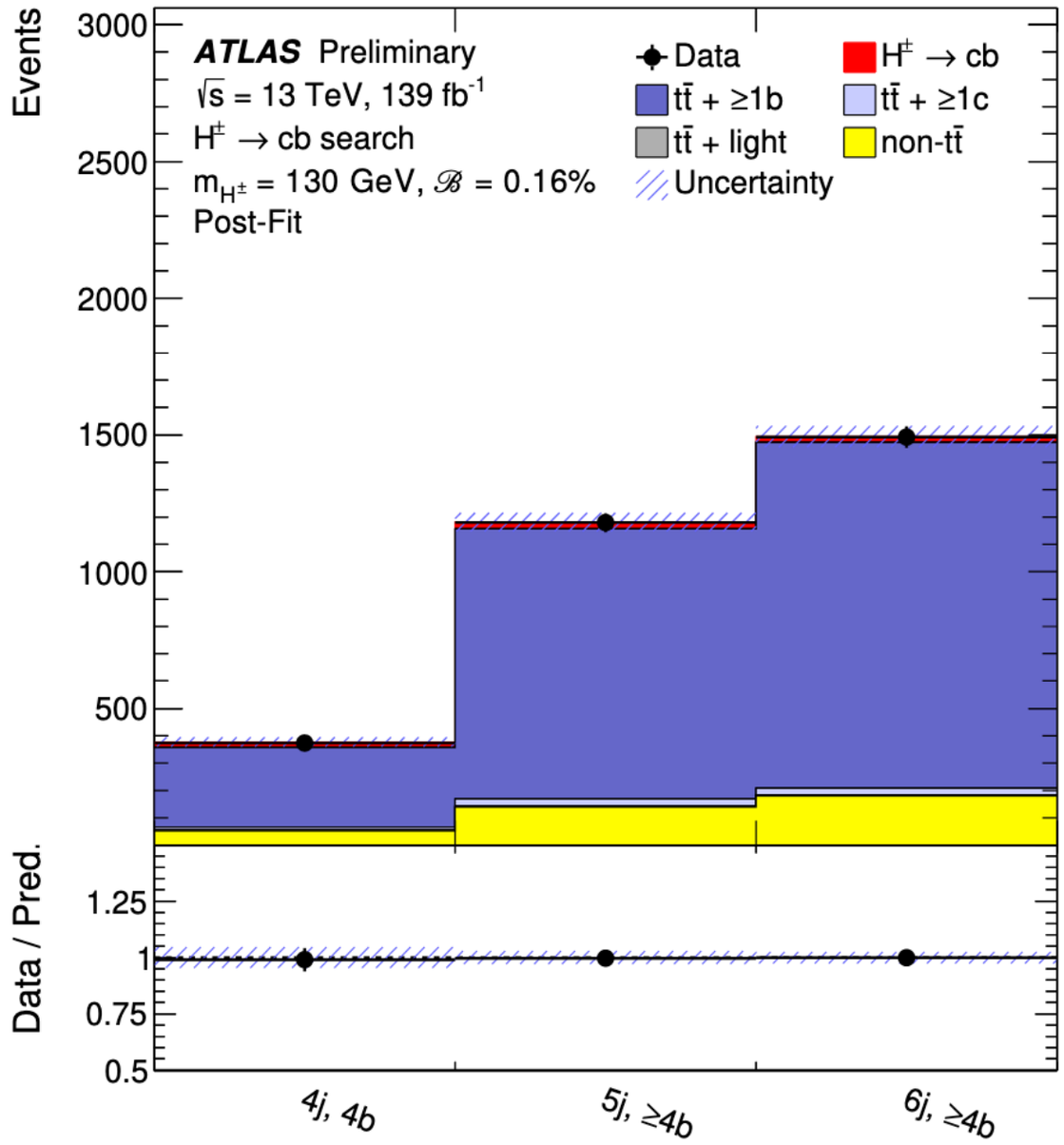


NN score

$H^{\pm} \to cb$ Pre-fit vs Post-fit

C. Hayes





$H^{\pm} \to aW^{\pm}, a \to \mu\mu$

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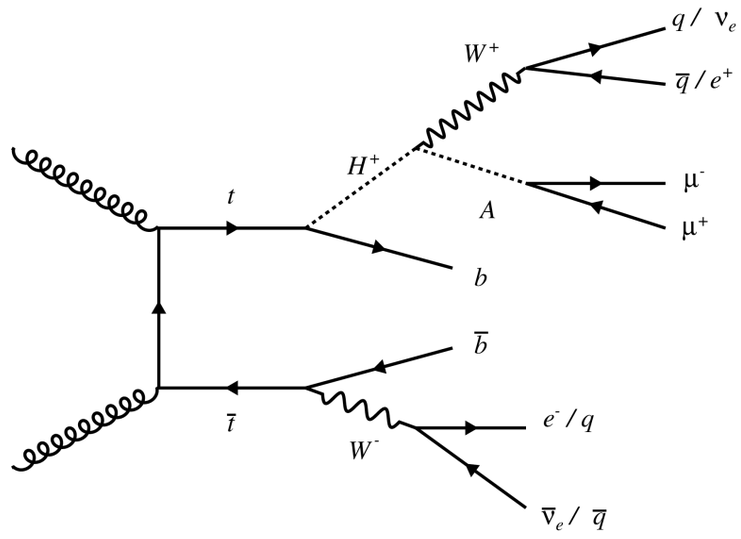
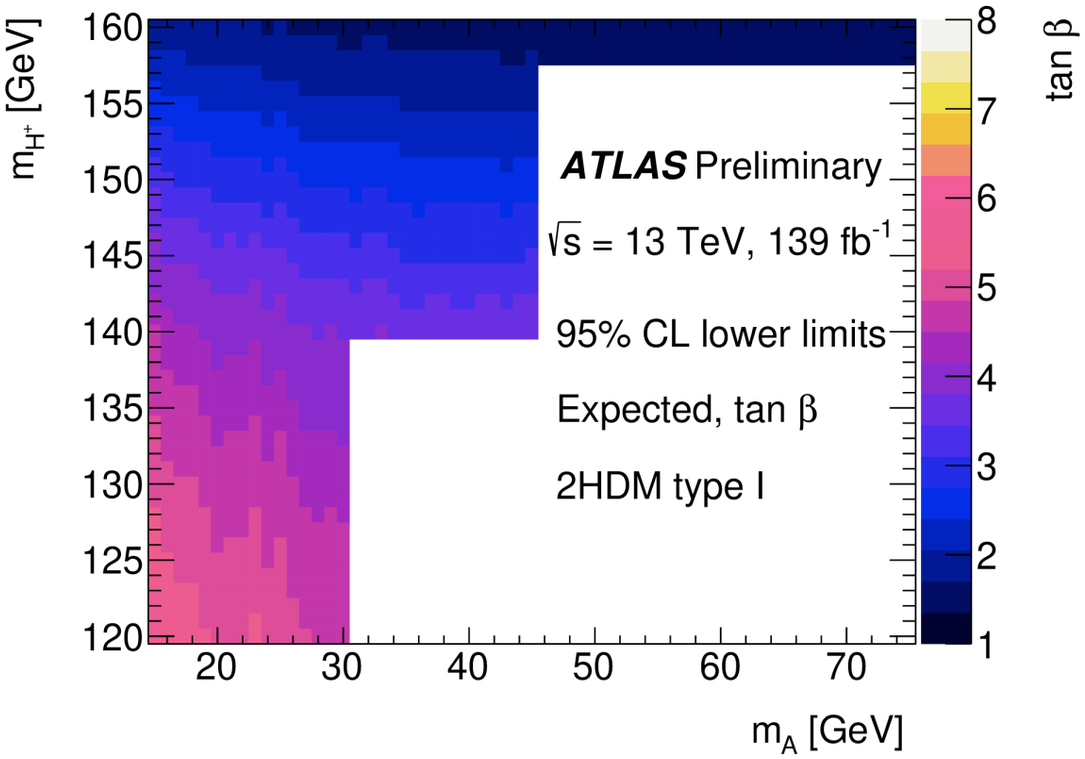
- In models where $H^{\pm} \to aW^{\pm}$ is allowed, branching ratios to fermionic states ($\tau\nu$, cs) can be suppressed.

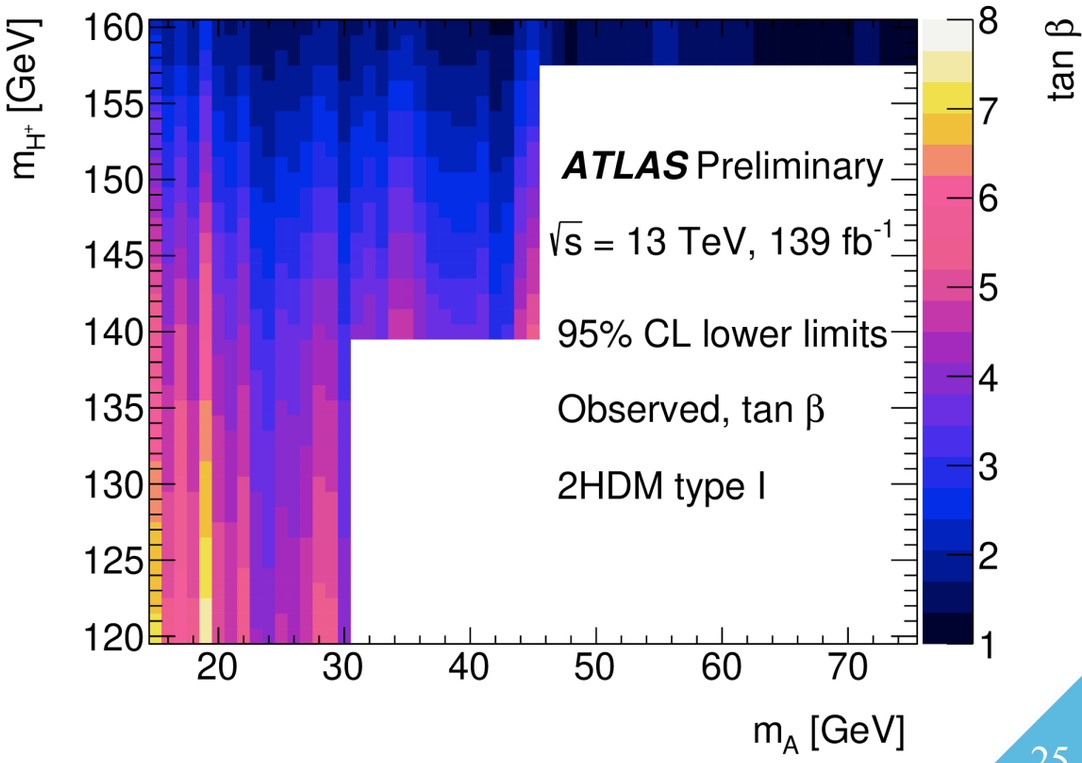
- Search for low mass $H^{\pm}$, a in $t\bar{t}$ decays in events with 1 electron, two muons, and 3 jets (1 b-jet)

- Search performed in $15 < m_{\mu\mu} < 75$ GeV region.



- Limits also provided on tan β in Type-I 2HDM scenarios





ATLAS EXPERIMENT

Double-Sided Crystal Ball

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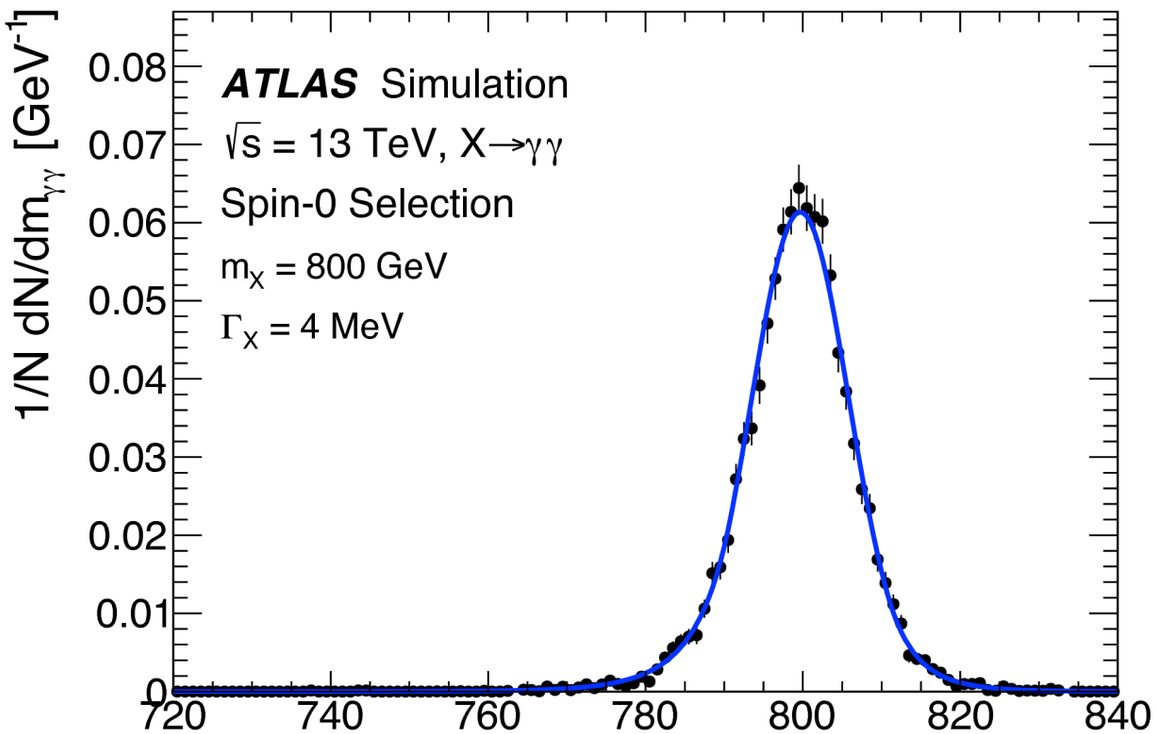
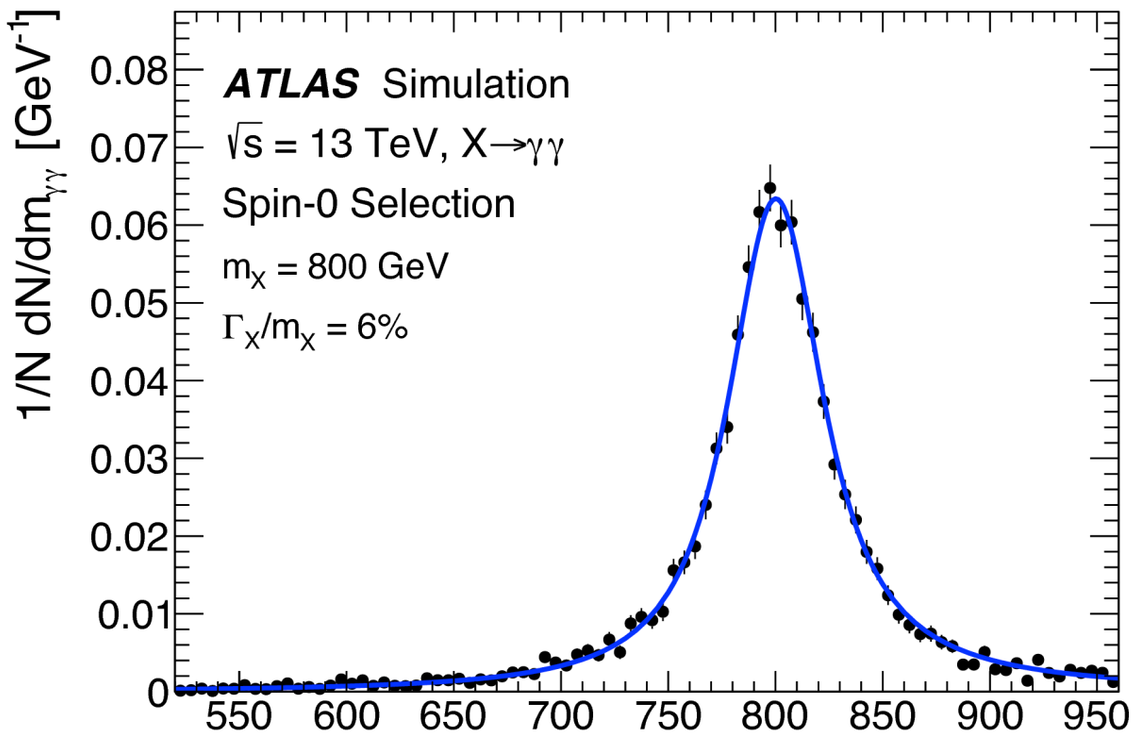




Convolved with BW fcn for larger widths

$$N \cdot \begin{cases} e^{-0.5t^2} & \text{if } -\alpha_{\text{low}} \le t \le \alpha_{\text{high}} \\ e^{-0.5\alpha_{\text{low}}^2} \left[\frac{\alpha_{\text{low}}}{n_{\text{low}}} \left(\frac{n_{\text{low}}}{\alpha_{\text{low}}} - \alpha_{\text{low}} - t \right) \right]^{-n_{\text{low}}} & \text{if } t < -\alpha_{\text{low}} \\ e^{-0.5\alpha_{\text{high}}^2} \left[\frac{\alpha_{\text{high}}}{n_{\text{high}}} \left(\frac{n_{\text{high}}}{\alpha_{\text{high}}} - \alpha_{\text{high}} + t \right) \right]^{-n_{\text{high}}} & \text{if } t > \alpha_{\text{high}}, \end{cases}$$

$$t = (m_{\gamma\gamma} - \mu_{\text{CB}})/\sigma_{\text{CB}}$$

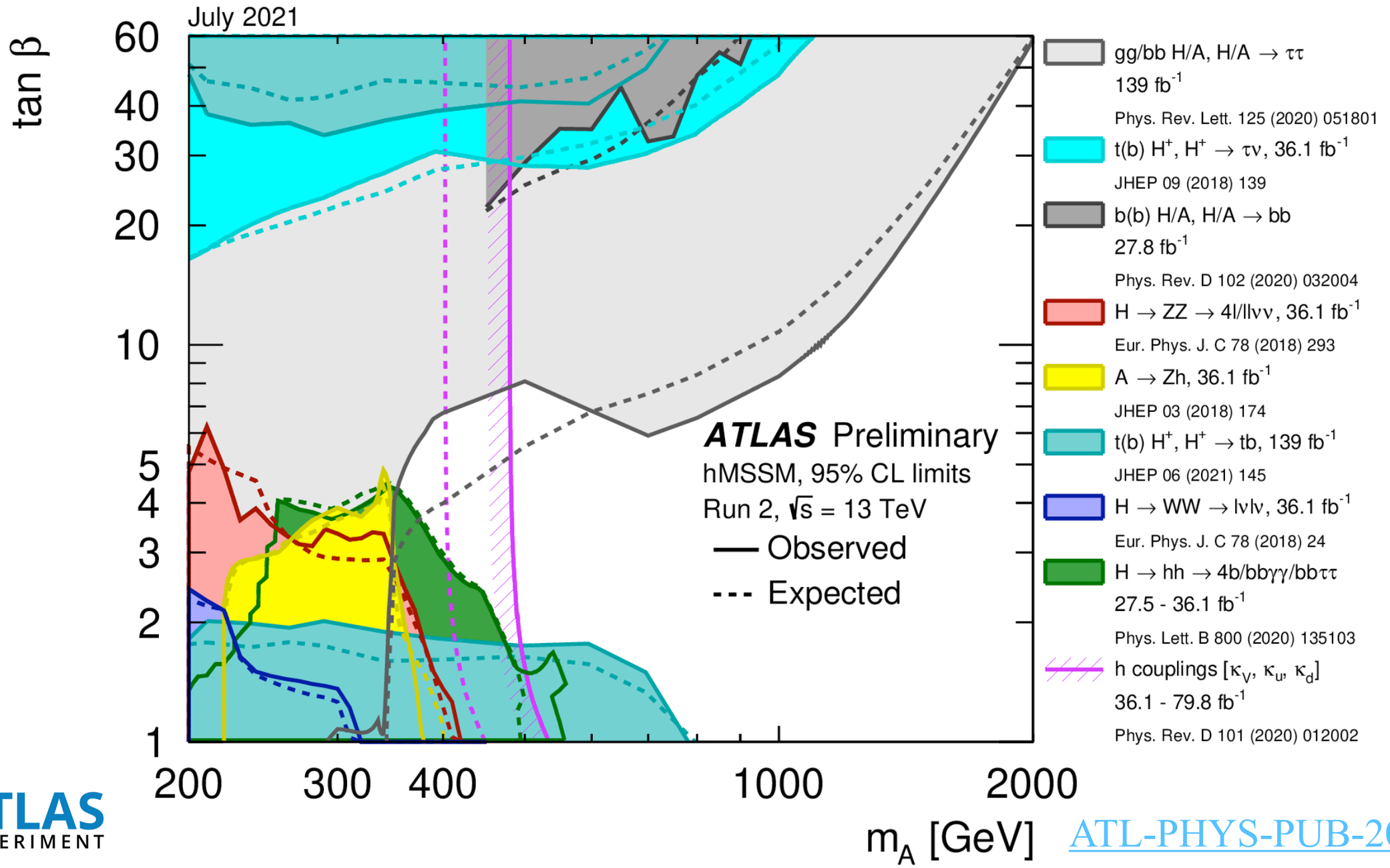
ATLAS EXPERIMENT

Run 2 Summaries: hMSSM

C. Hayes

- High-mass resonance searches are able to constrain new physics.
  Here, use the hMSSM as a benchmark (tree-level dependencies on m_A & tan β).

- Direct searches for $H \to \tau\tau$ providing best constraints at high m_A, tan β,
  with many channels providing complementary sensitivity at low m_A.



ATLAS EXPERIMENT

ATL-PHYS-PUB-2021-030