Searching for new symmetries in the Higgs sector with the ATLAS detector

DISCRETE 2022

Dominik Duda

9th November 2022

Motivation for an Extended Higgs Sector

- The Higgs mechanism of the SM is the most simple solution to establish electroweak symmetry breaking (EWSB)
  - **Many reasons for a non-minimal Higgs sector**
- An extended Higgs sector can solve some of the problems the SM fails to answer:
  - Provide new sources of CP violation
  - Enhance vacuum stability.
  - Provide a dark matter candidate.
  - Provide a solution to the strong CP problem ($\Longrightarrow$ axion)
- Models of new physics beyond the SM often require additional scalar Higgs states:
  - Two **Higgs doublets** are required in the minimal supersymmetric extension of the SM (MSSM)
  - **Higgs triplets** are required in models with a type-I or type-II seesaw mechanism

Extended Higgs sector

2 Higgs doublets (i.e. 2HDM) → **EWSB** → **h, H, A, $H^{\pm}$**

- **Relevant model parameters:**
  - Mixing angle α between neutral states
  - tan β (ratio of VEVs)
  - Masses: m_h, m_H, m_A, $m_{H^{\pm}}$

Phys.Rev.D 67 (2003) 075019

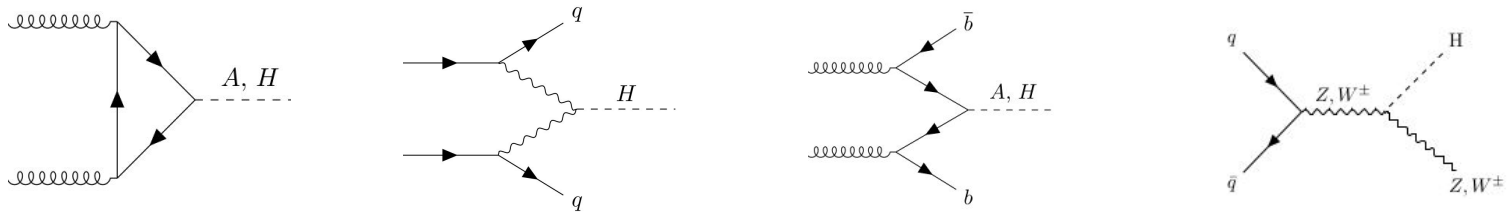
1 Higgs doublet + 2 triplets (Georgi-Machacek model) → **EWSB** → **h, H, H_3, $H^{\pm}_3$, H_5, $H^{\pm}_5$, $H^{\pm\pm}_5$**

- **Relevant model parameters:**
  - Mixing angle α between neutral states
  - $s_H = \sin\theta_H$ (ratio of doublet and triplet VEVs)
  - Masses: m_h, m_H, m_{H3}, m_{H5}

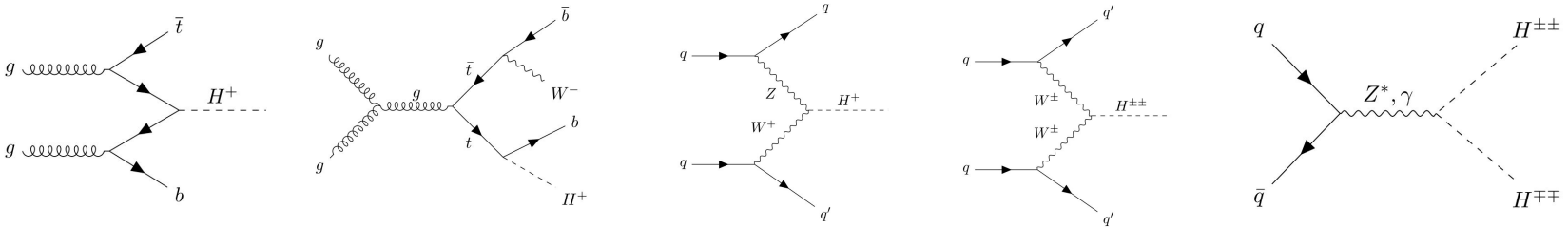
Phys.Rev.D 90 (2014) 1

Outline

- ATLAS performs a wide range of searches for additional Higgs bosons
  - **Neutral heavy/light Higgs bosons**



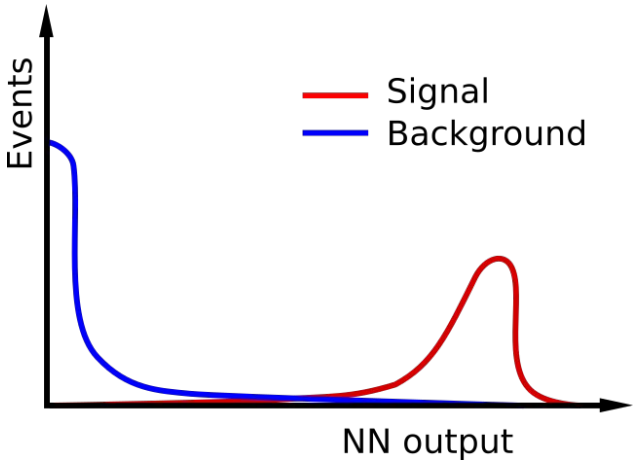
  - **Charged Higgs bosons**

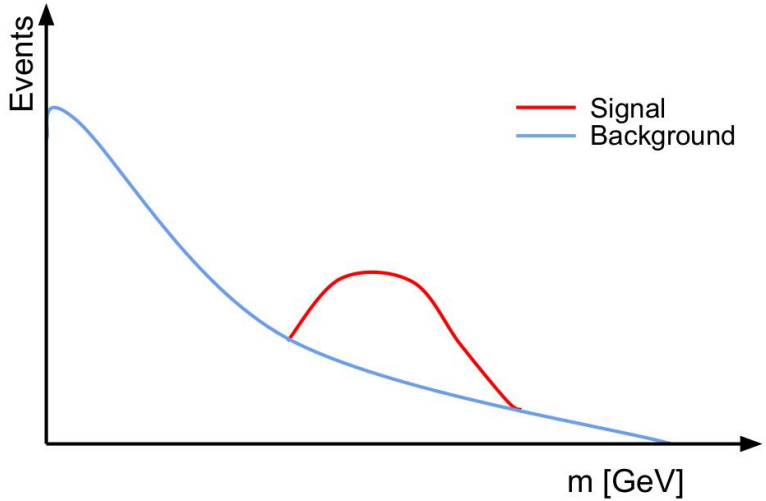


  - **Exotic decays of the already discovered Higgs boson**
    - $h \rightarrow a\,a$
    - $h \rightarrow Z_d\,Z_d$
    - $h \rightarrow \ell\tau$

Search strategy

- Most analyses are designed to perform (quasi) **model-independent searches for a narrow bump in a smoothly falling mass spectrum**
  - Perform maximum likelihood fit to **set upper limits** on production cross section and/or branching fraction
  - Interpretation in a large variety of different models



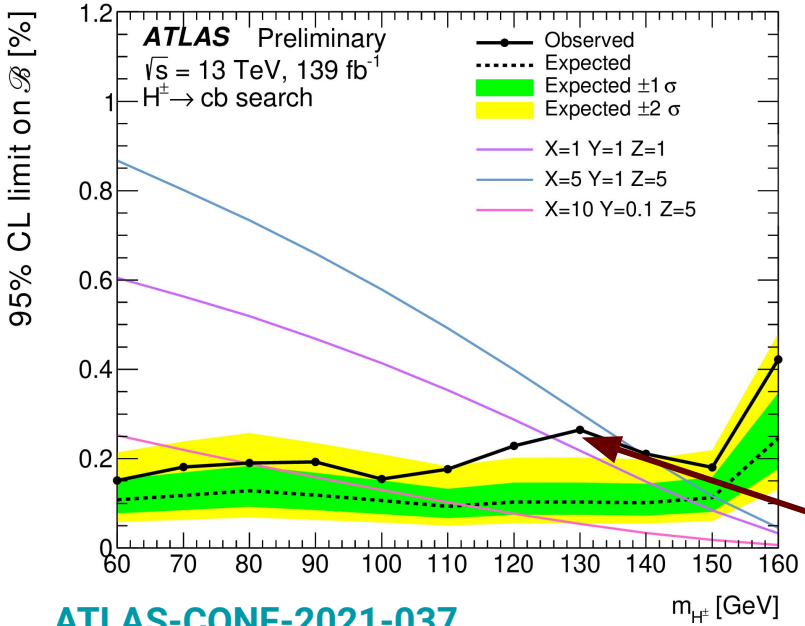


- For complex final states, train neural networks (NNs) or boosted decision trees (BDTs) to separate signal from backgrounds
  - Probe BDT/NN response distribution

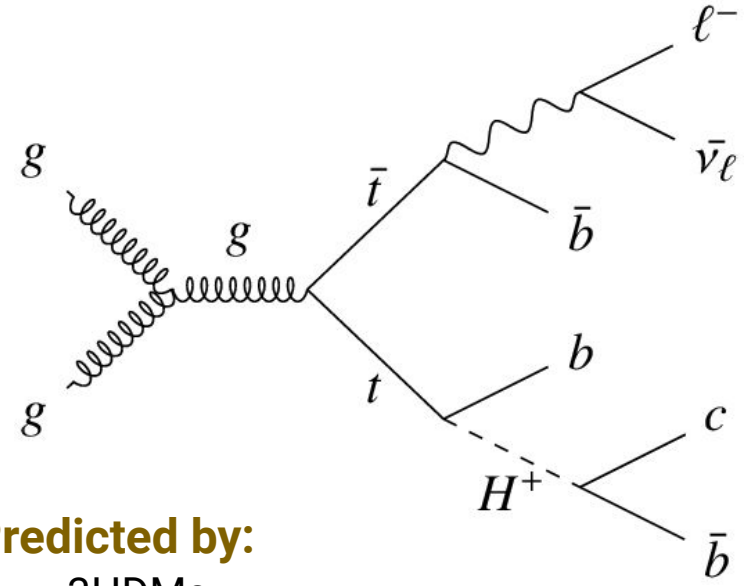
Search for additional Higgs bosons

Search for a charged scalar in top-quark decays

- **Final state:**
  - Charged lepton, missing transverse energy and at least four jets
- **Decay of scalar:** $H^+ \rightarrow bc$



ATLAS-CONF-2021-037

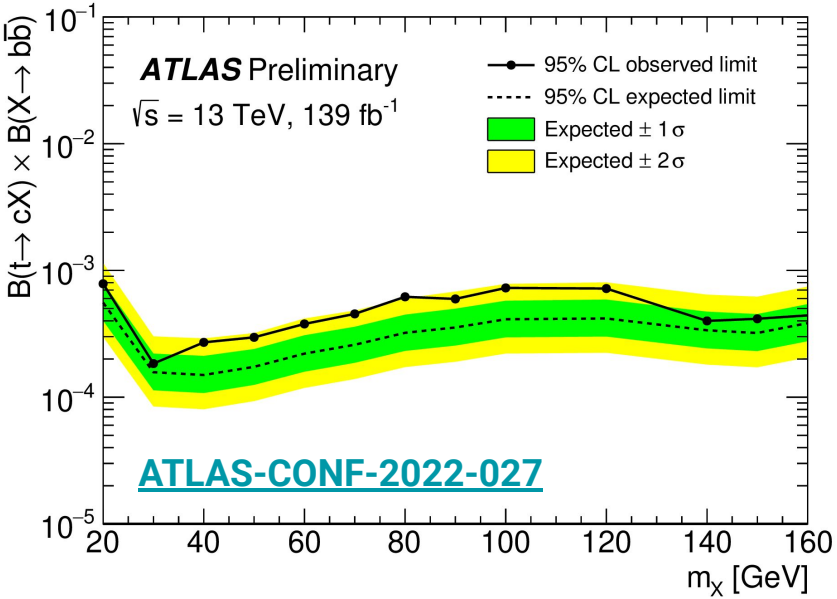


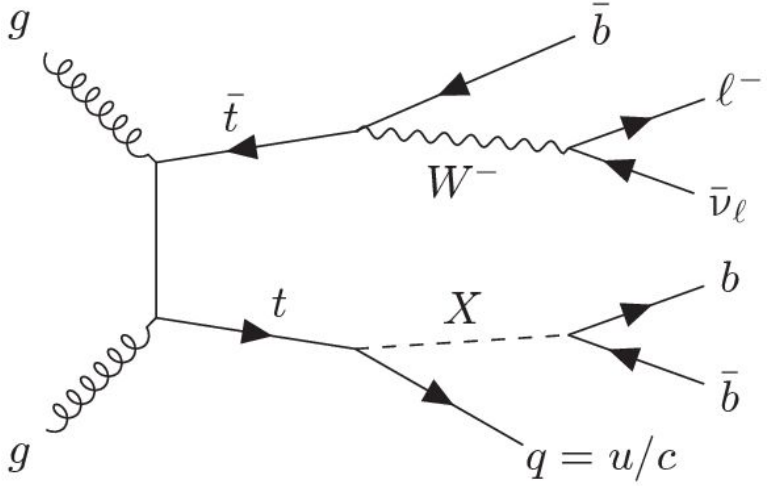
- **Predicted by:**
  - 3HDMs

Small excess with a local (global) significance of 3.0σ (1.6σ) for m_{H+} = 130GeV

Search for a new scalar resonance in top-quark decays

- **Final state:**
  - Charged lepton, missing transverse energy and at least four jets
- **Decay of scalar:** X → bb



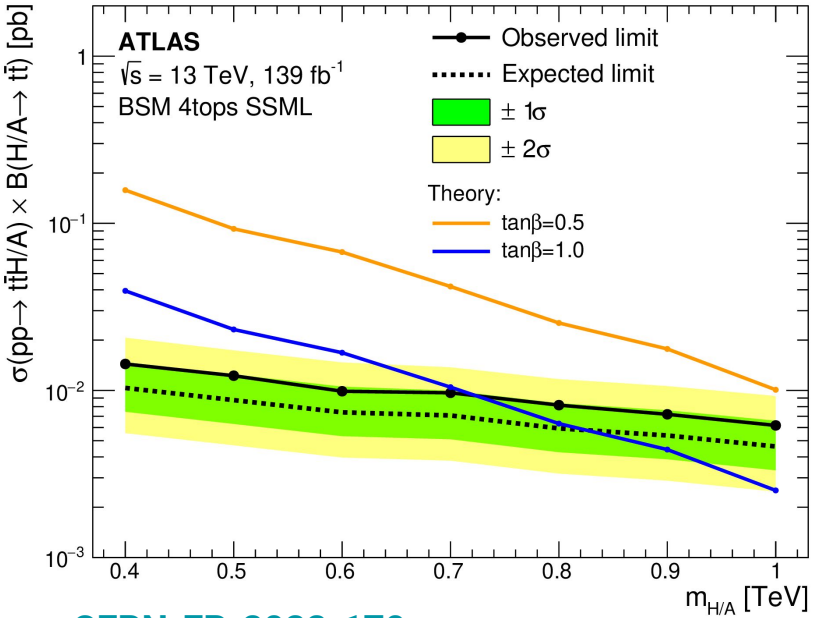


- **Predicted by:**
  - SUSY with R-parity violation
  - Composited Higgs
  - ALP models

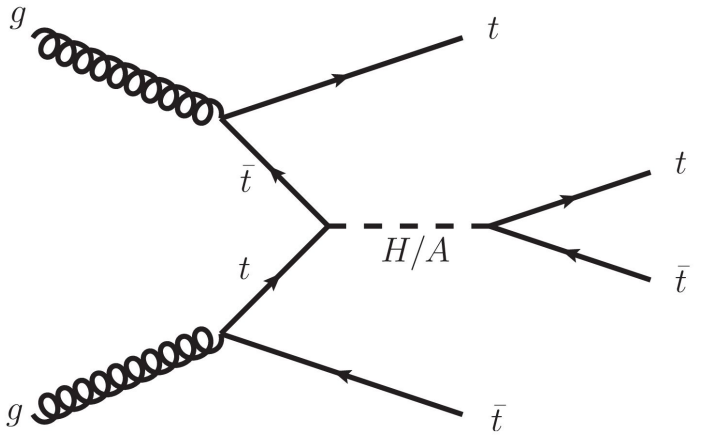
See small excess with a local significance of around 2.0σ over almost the entire range of m_X

Search for new scalar resonances in 4 top events

- **Final state:**
  - Two (same-sign) or three charged leptons
  - 4 b-jets
  - 2 or 4 light-flavour jets



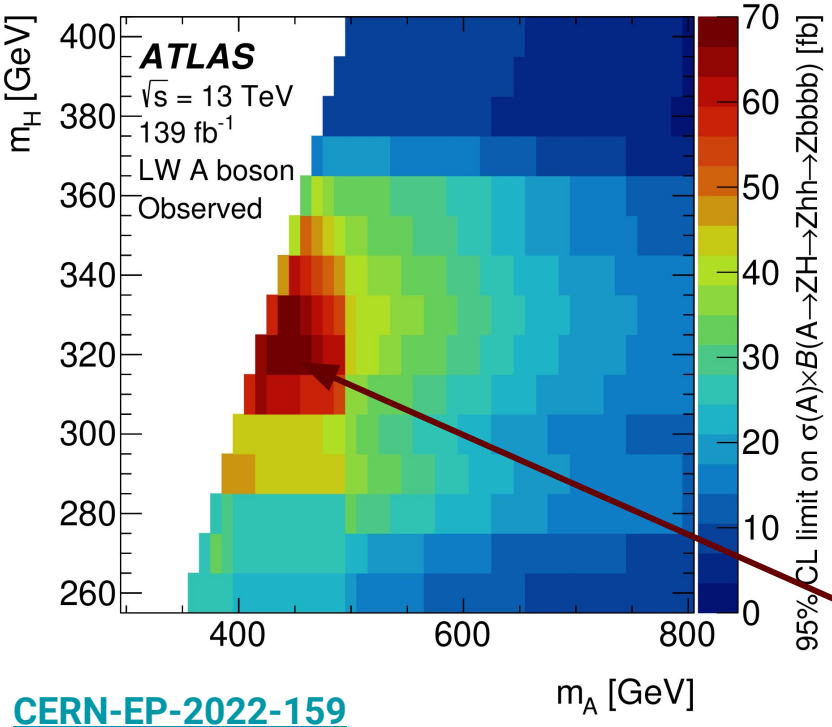
[CERN-EP-2022-170]

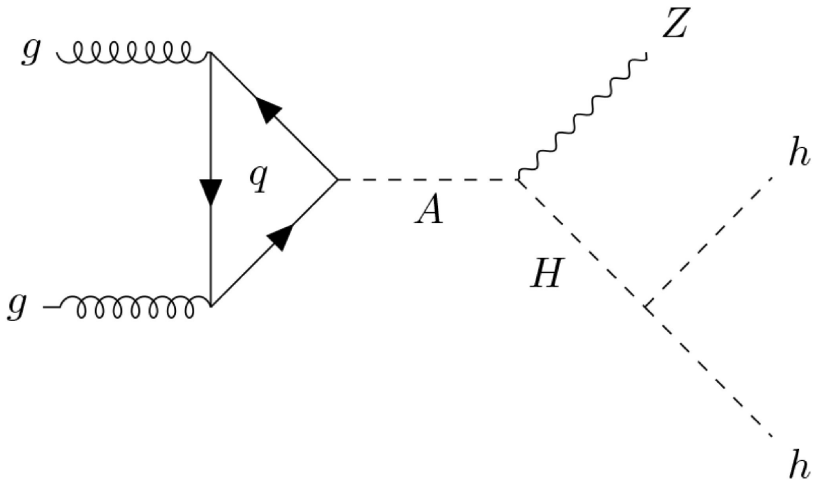


- **Decay:** A/H → tt
- **Predicted by:**
  - 2HDM

Search for Higgs boson pair production in association with a vector boson

- **Final state:**
  - Two charged leptons and 4 b-jets
  - Missing transverse energy and 4 b-jets





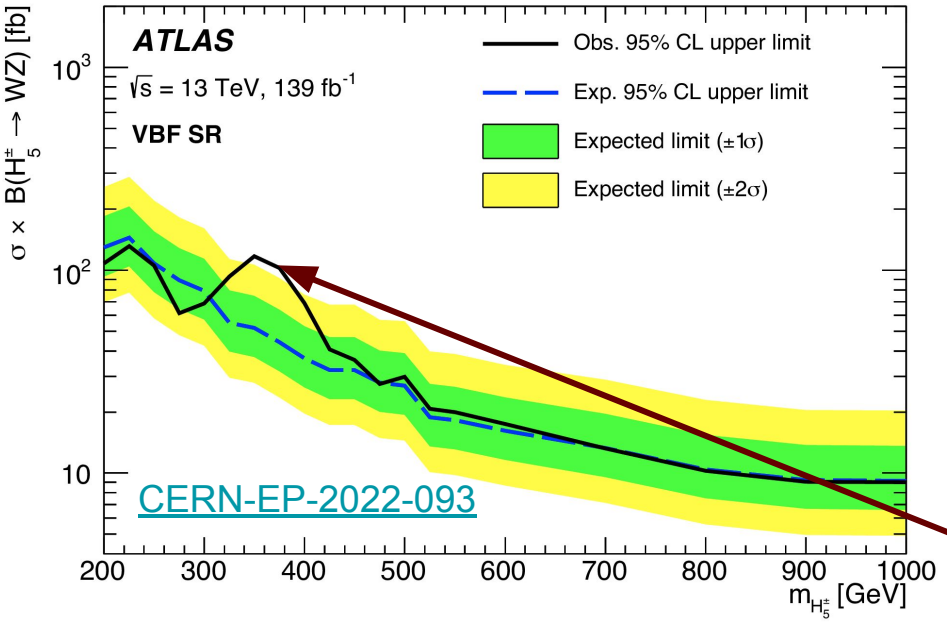
- **Decay of scalar:**
  - $A \rightarrow ZH \rightarrow Zhh \rightarrow \ell\ell bbbb, \nu\nu bbbb$
- **Predicted by:**
  - 2HDMs

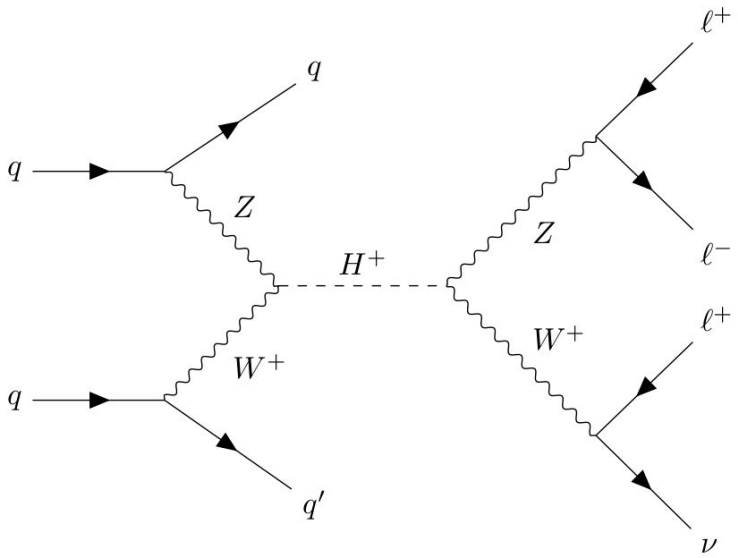
See small excess with a local (global) significance of 3.8σ (2.8σ) at (m_A, m_H) = (420, 320) GeV

CERN-EP-2022-159

Search for fermiophobic singly charged Higgs bosons

- **Final state:**
  - Three charged lepton
  - Missing transverse energy
  - Two jets (in forward direction)



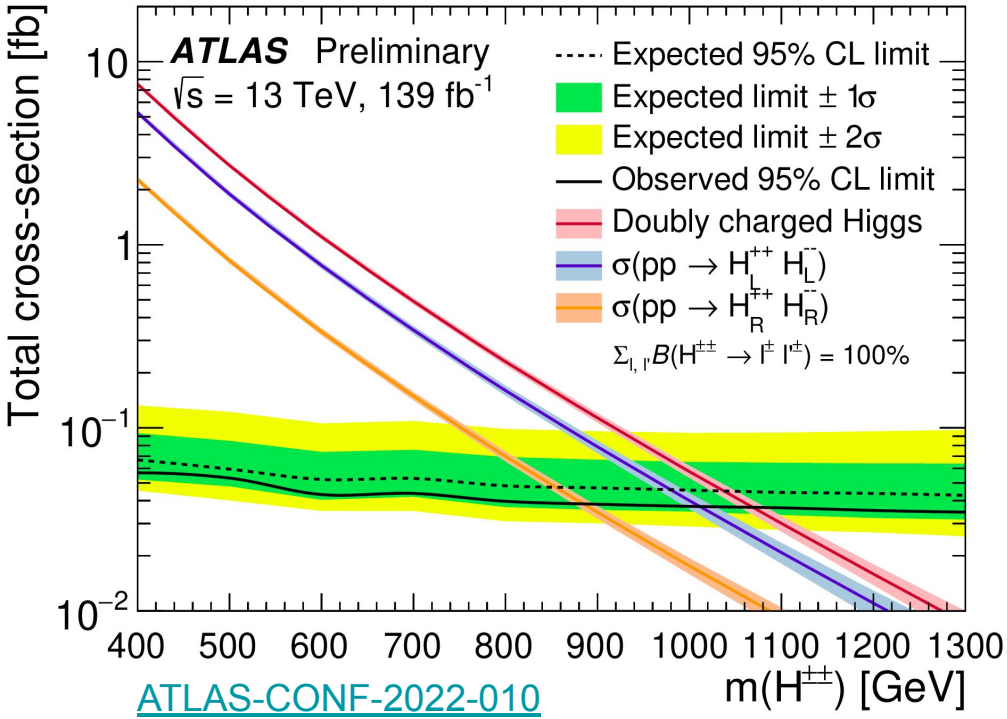


- **Decay:** $H^+ \rightarrow WZ \rightarrow \ell\nu\ell\ell$
- **Predicted by:**
  - Higgs triplet models (i.e. GM model)

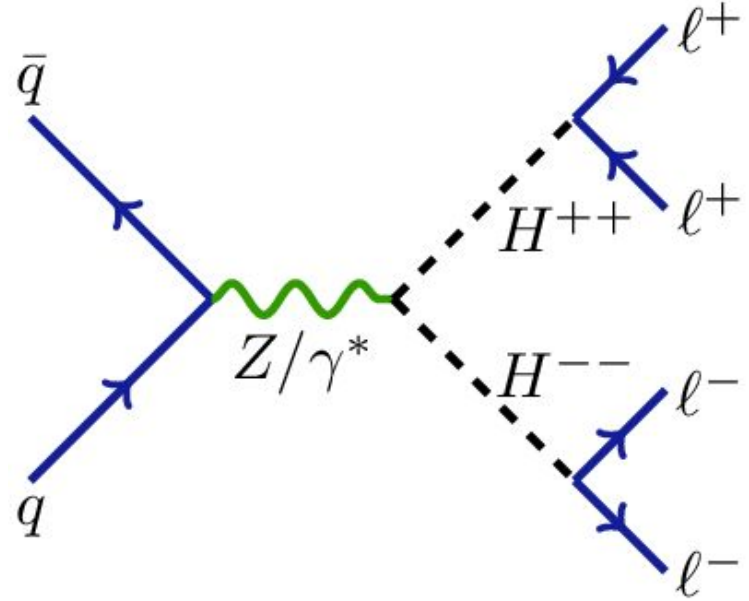
Small excess with a local (global) significance of 2.8σ (1.6σ) for m_{H+} = 375GeV

Search for doubly charged Higgs boson production

- **Final state:**
  - Four charged lepton



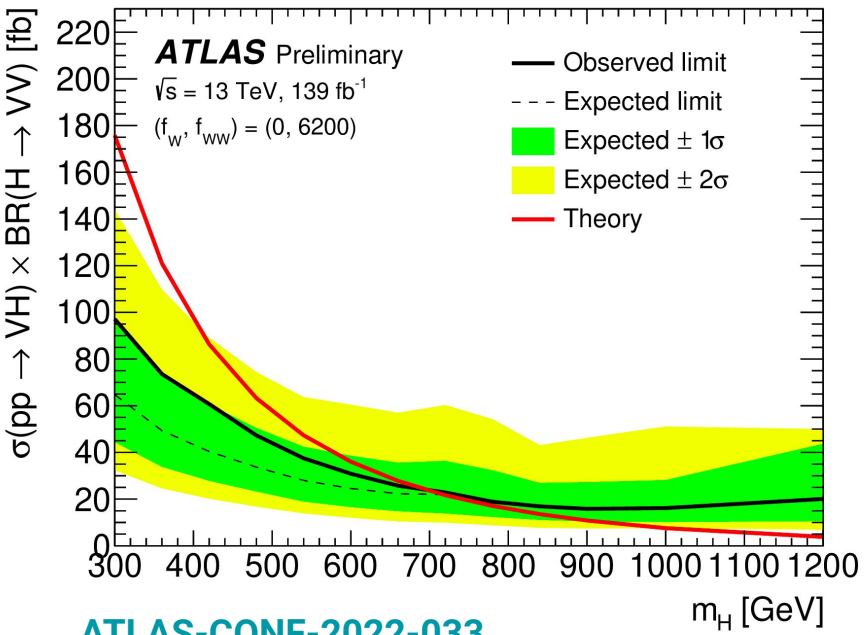
ATLAS-CONF-2022-010



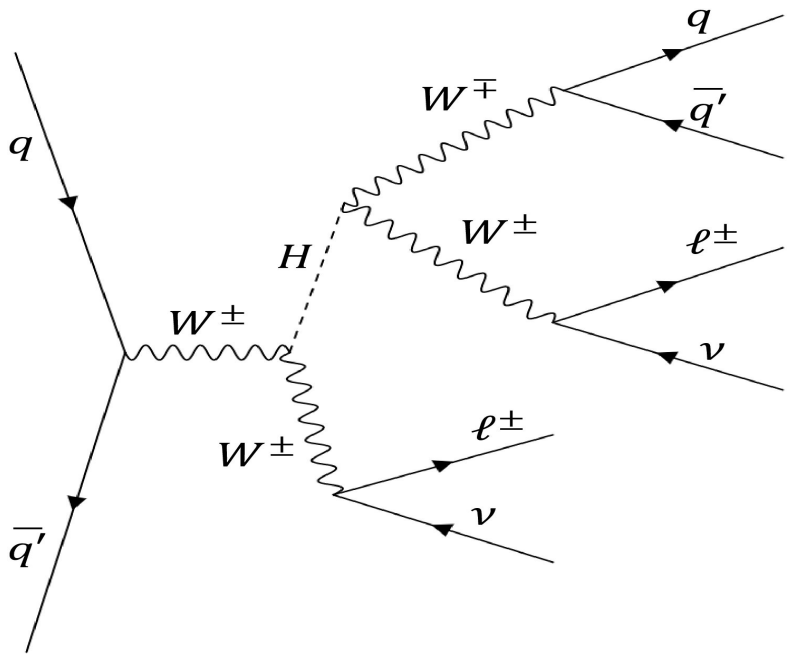
- **Decay:** $H^{++} \rightarrow \ell^+\ell^+$
- **Predicted by:**
  - Left-right symmetric models
  - Type-II seesaw models

Search for a heavy Higgs boson produced via WH

- **Final state:**
  - Two charged leptons (same sign)
  - Missing transverse momentum
  - Two small-R jets or 1 large-R jet

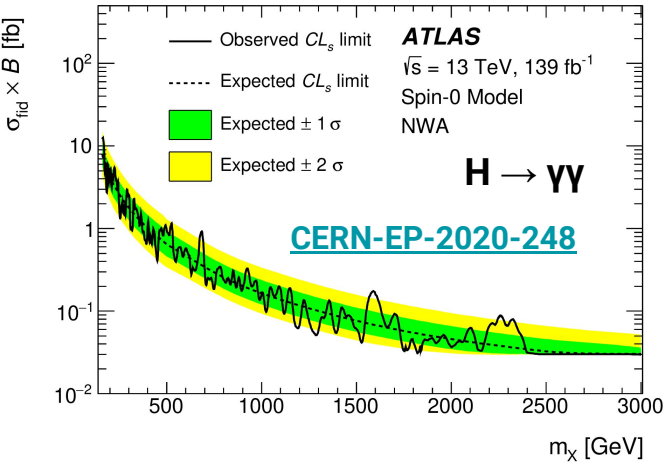


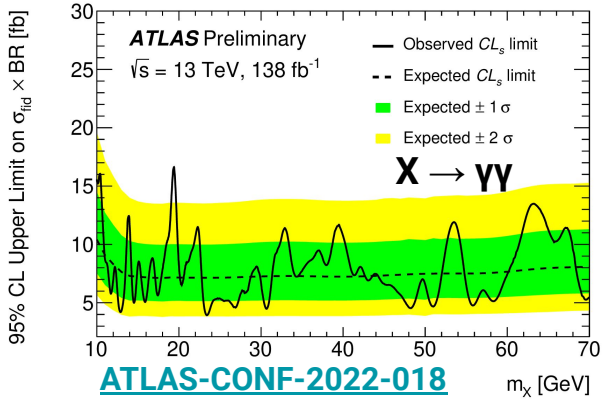
[ATLAS-CONF-2022-033]

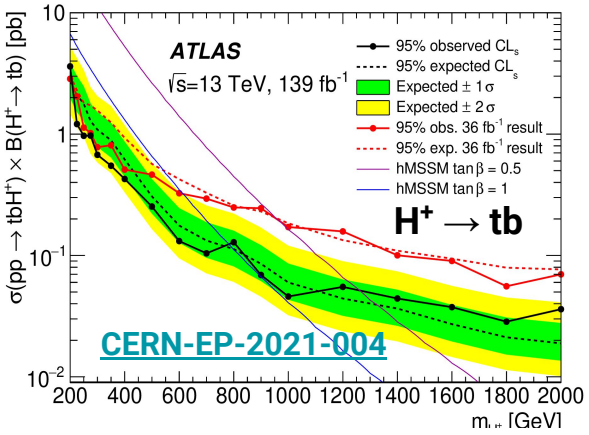


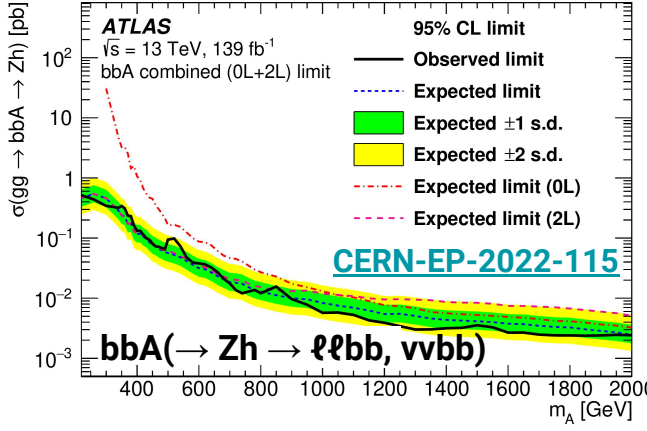
- **Decay:** H → WW → ℓνjj
- **Predicted by:**
  - 2HDMs

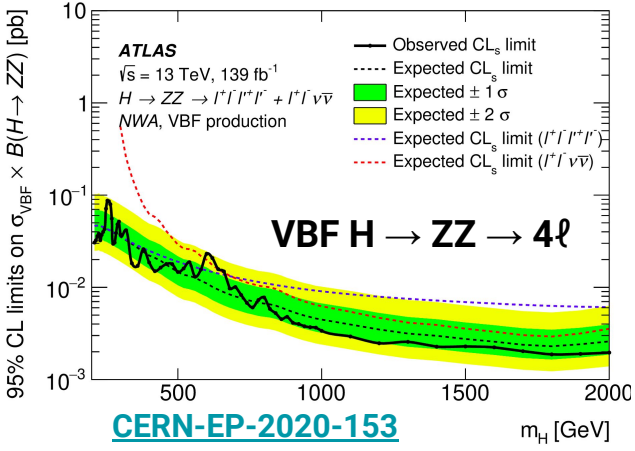
Many more results

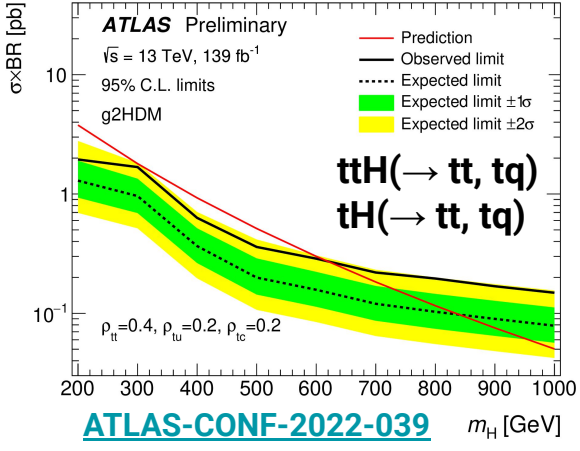


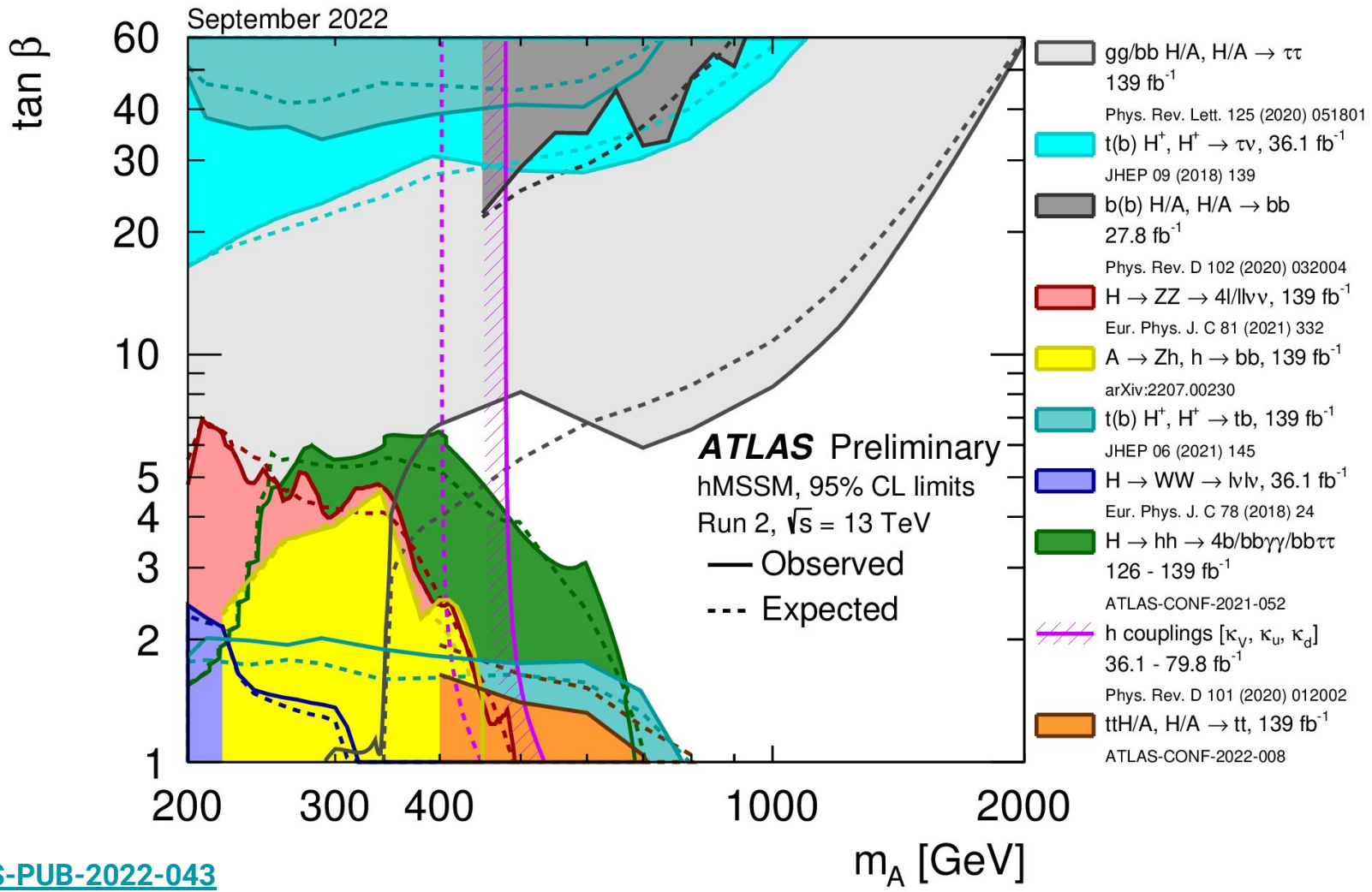










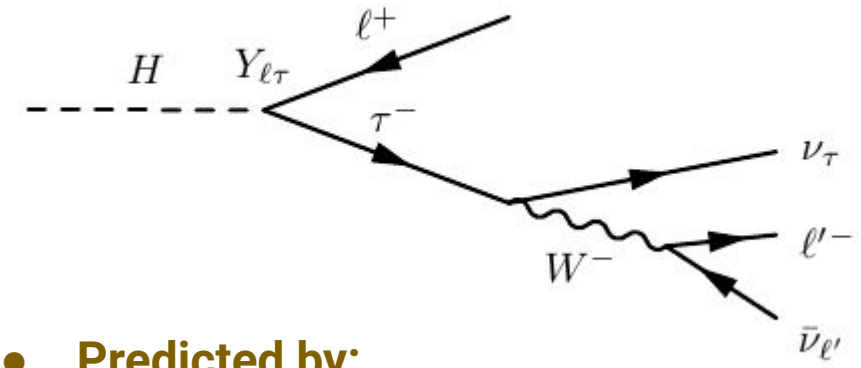


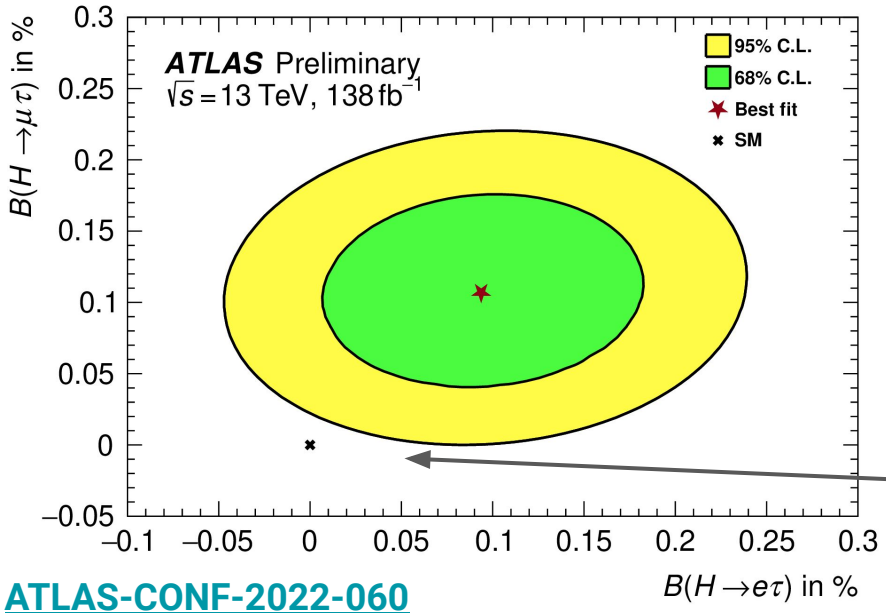
ATL-PHYS-PUB-2022-043

Search for exotic Higgs boson decays

Searches for lepton-flavour-violating decays of the Higgs boson

- **Considered production modes:**
  - ggF, VBF, Higgs-Strahlung
- **Decays:**
  - $\ell\tau_{\ell}$ and $\ell\tau_{had}$ (with ℓ = e, μ)





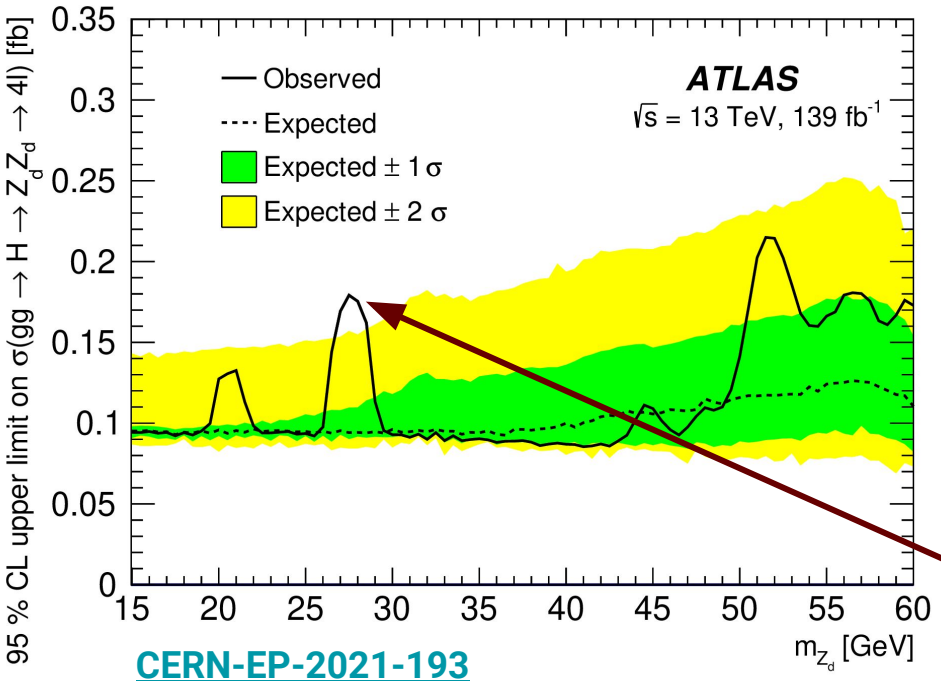
- **Predicted by:**
  - Flavour-violating 2HDMs
- Particularly interesting due to flavour anomalies observed by **g − 2** and **LHCb** experiments

Results are consistent to SM predictions within 2.1σ

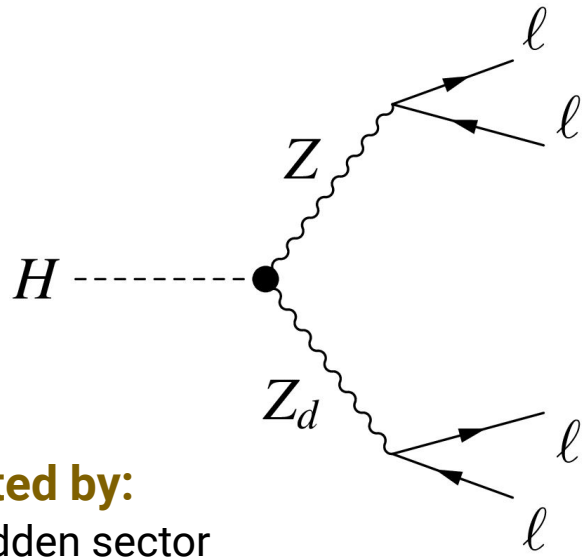
ATLAS-CONF-2022-060

Search for Higgs bosons decaying into new spin-0 or spin-1 particles

- **Final state:** 4μ
- **Decays:**
  - $h \to Z_d Z_d$, $h \to Z_d Z$, $h \to a\,a$, $h \to h_s\,h_s$

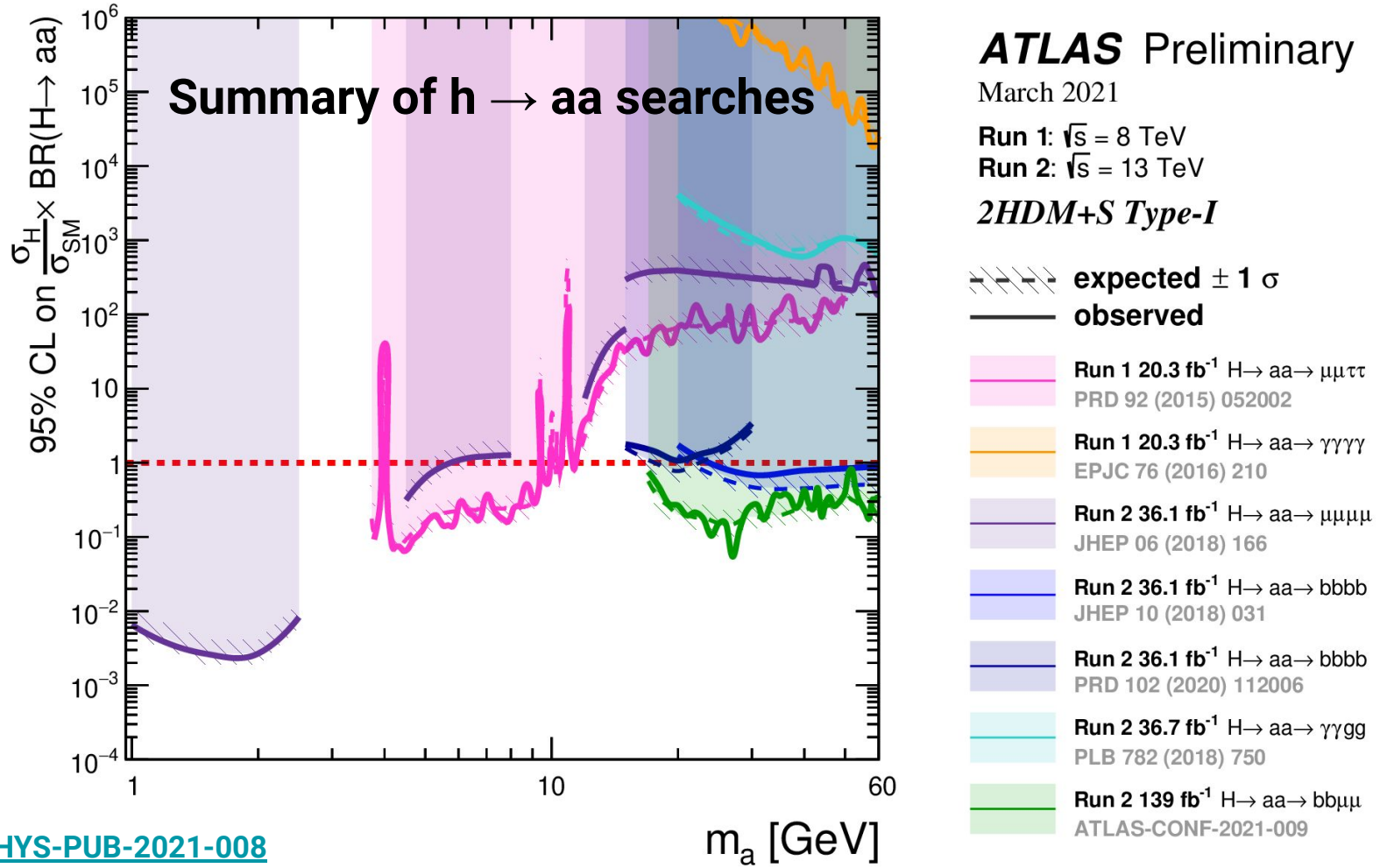


CERN-EP-2021-193



- **Predicted by:**
  - Hidden sector
  - Dark Matter models
  - Next-to-Minimal Supersymmetric Standard Model

Small excess with a local significance of 2.5σ for m_{Zd} = 28GeV



ATL-PHYS-PUB-2021-008

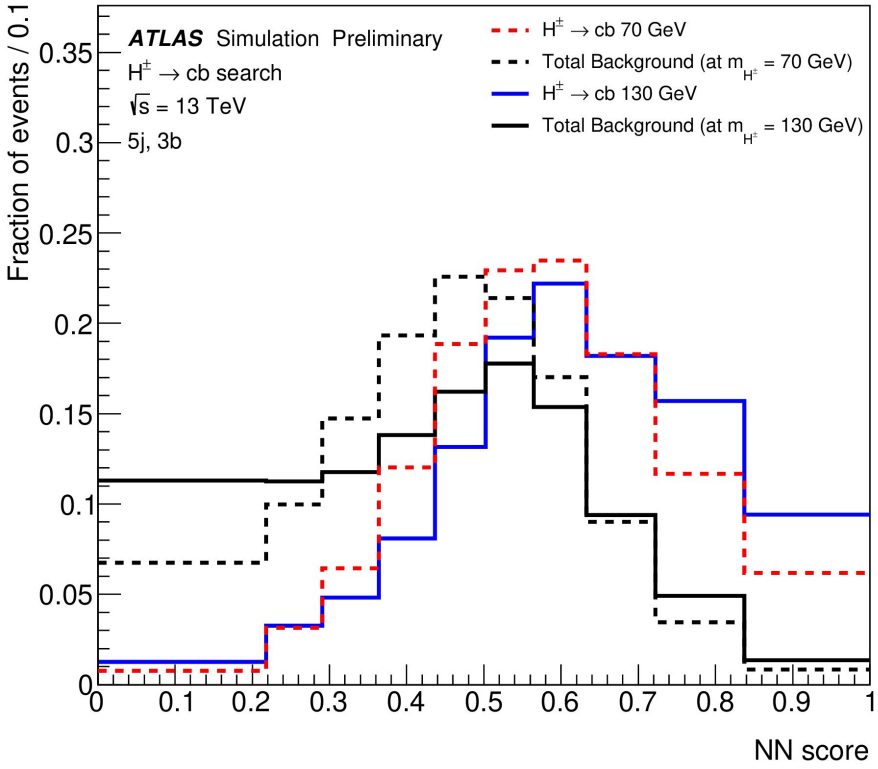
Concluding remarks

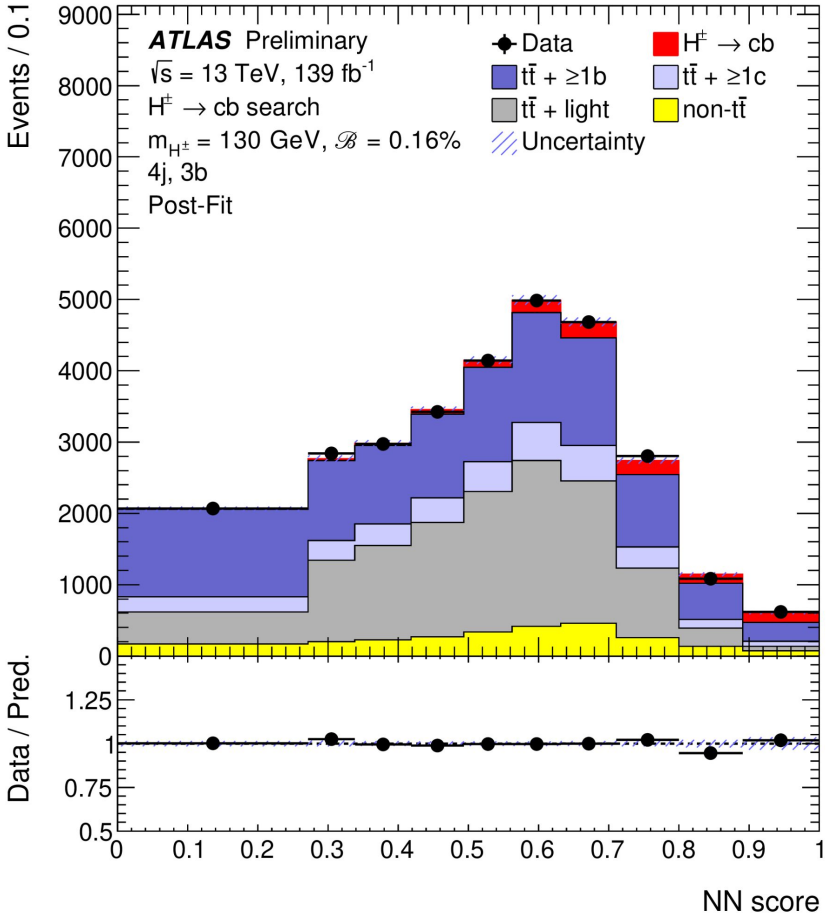
- **Extended Higgs sector is promising to find new physics**
- **Many interesting searches for additional Higgs bosons and exotic Higgs boson decays are performed by ATLAS**
  - Presented only a few highlights of available results:
    - Additional results can be found via the **ATLAS** publication pages
  - No significant hint for physics beyond the SM has been observed so far
    - But there are several small deviations that have to be followed up
  - Many further results based on the full Run-2 data set are expected in the next months

- Efforts will be continued in Run 3 (and eventually at HL-LHC)
  - New production and decay channels become available due to increased dataset size

Back-up

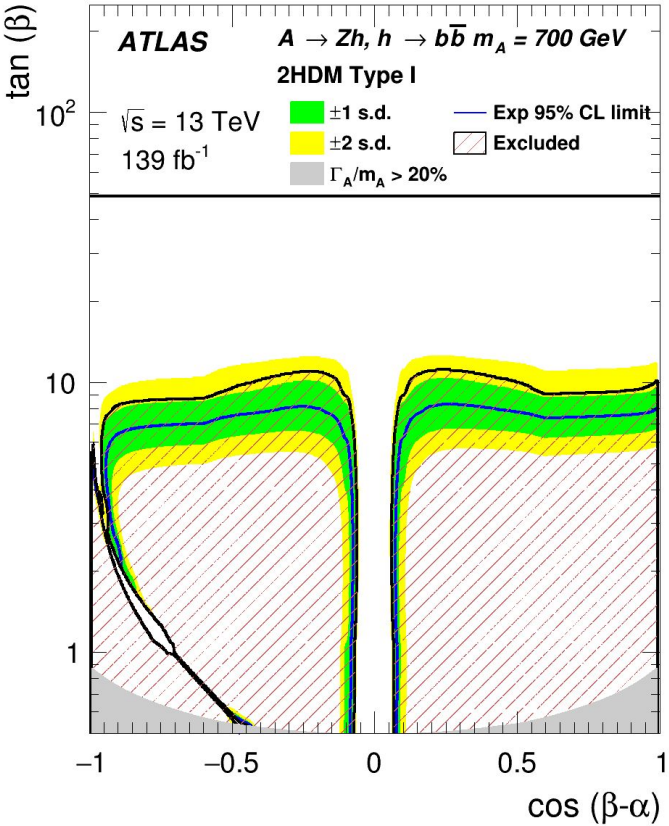
Search for a charged scalar in top-quark decays

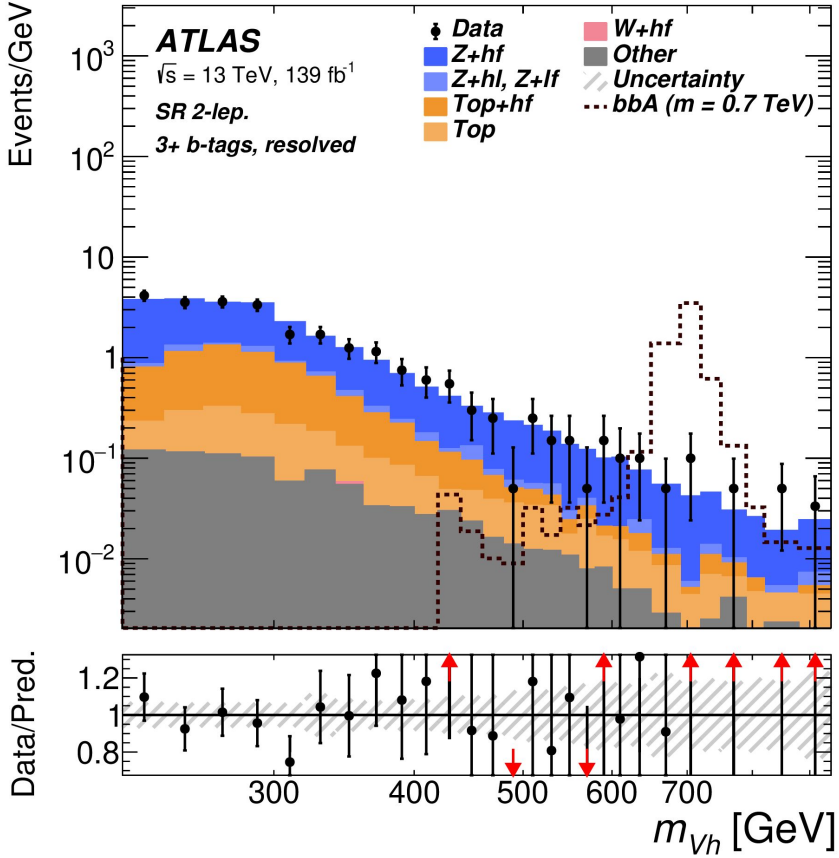




[ATLAS-CONF-2021-037]

Search for heavy pseudoscalars

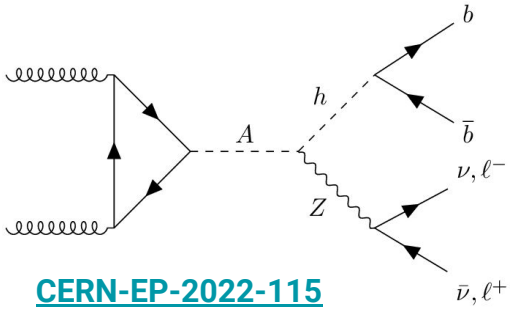


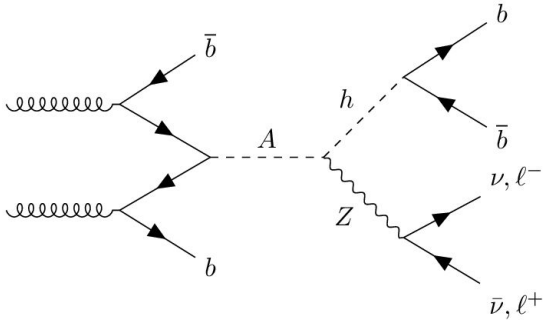


CERN-EP-2022-115

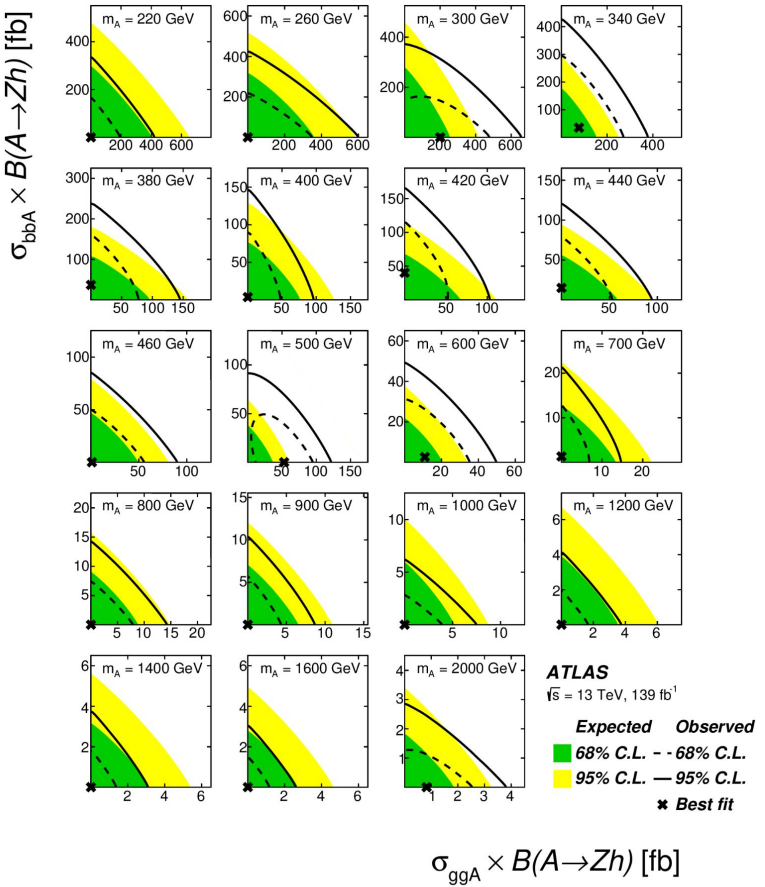
Search for heavy pseudoscalars

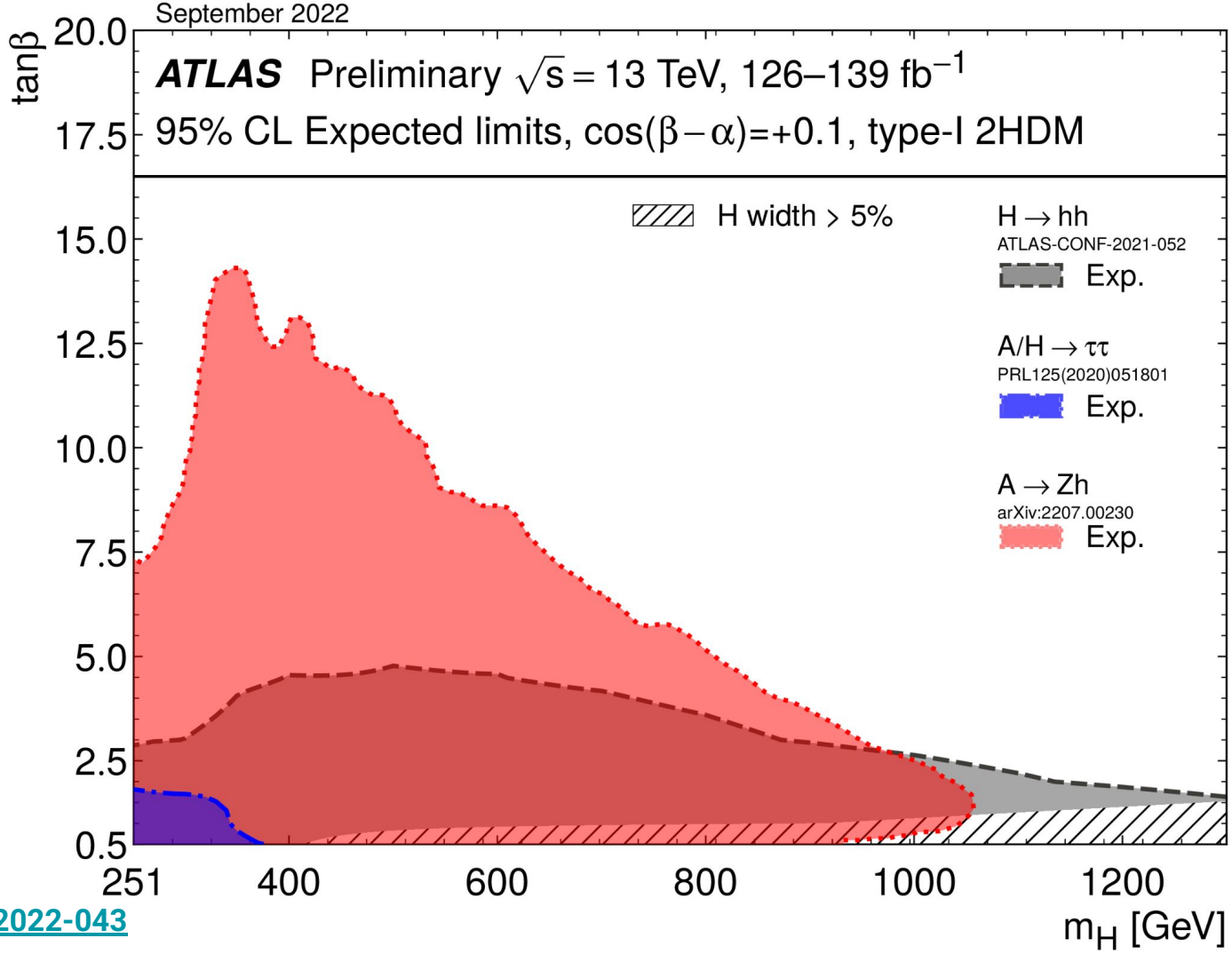
- **Final state:**
  - Low mass:
    - Two charged leptons and up to 2 (4) b-jets
  - High mass:
    - Missing transverse energy and up to 2 (4) b-jets
- **Decay:** A → Zh → ℓℓbb, ννbb
- **Predicted by:**
  - 2HDMs, 3HDMs, Higgs triplets models, etc.





[CERN-EP-2022-115]

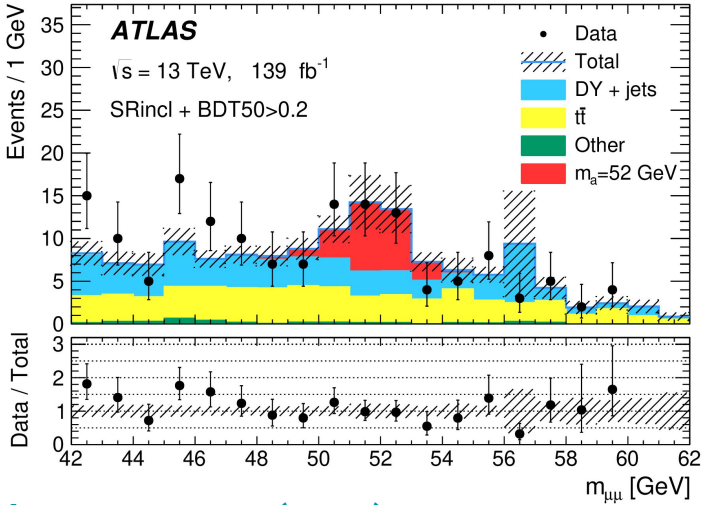


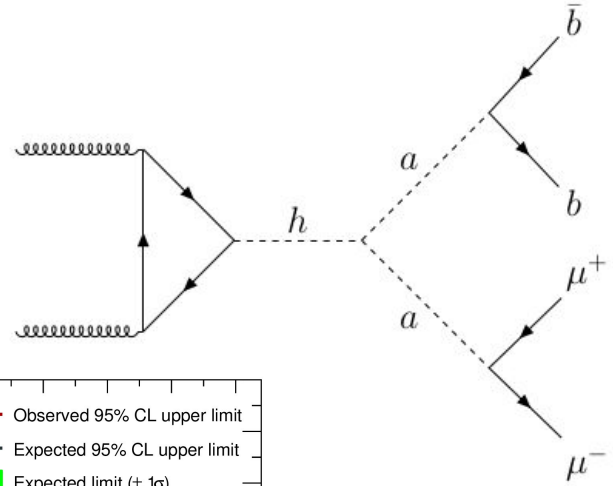


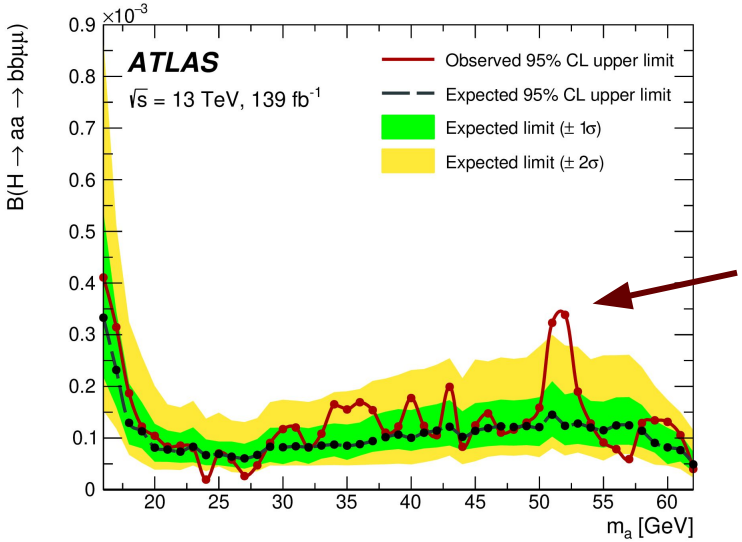
ATL-PHYS-PUB-2022-043

Search for Higgs boson decays into pseudoscalar particles

- **Final state:** μμbb
- **Decay of scalar:**
  - a → μμ, bb
- **Predicted by:**
  - ALP models
  - Dark matter models

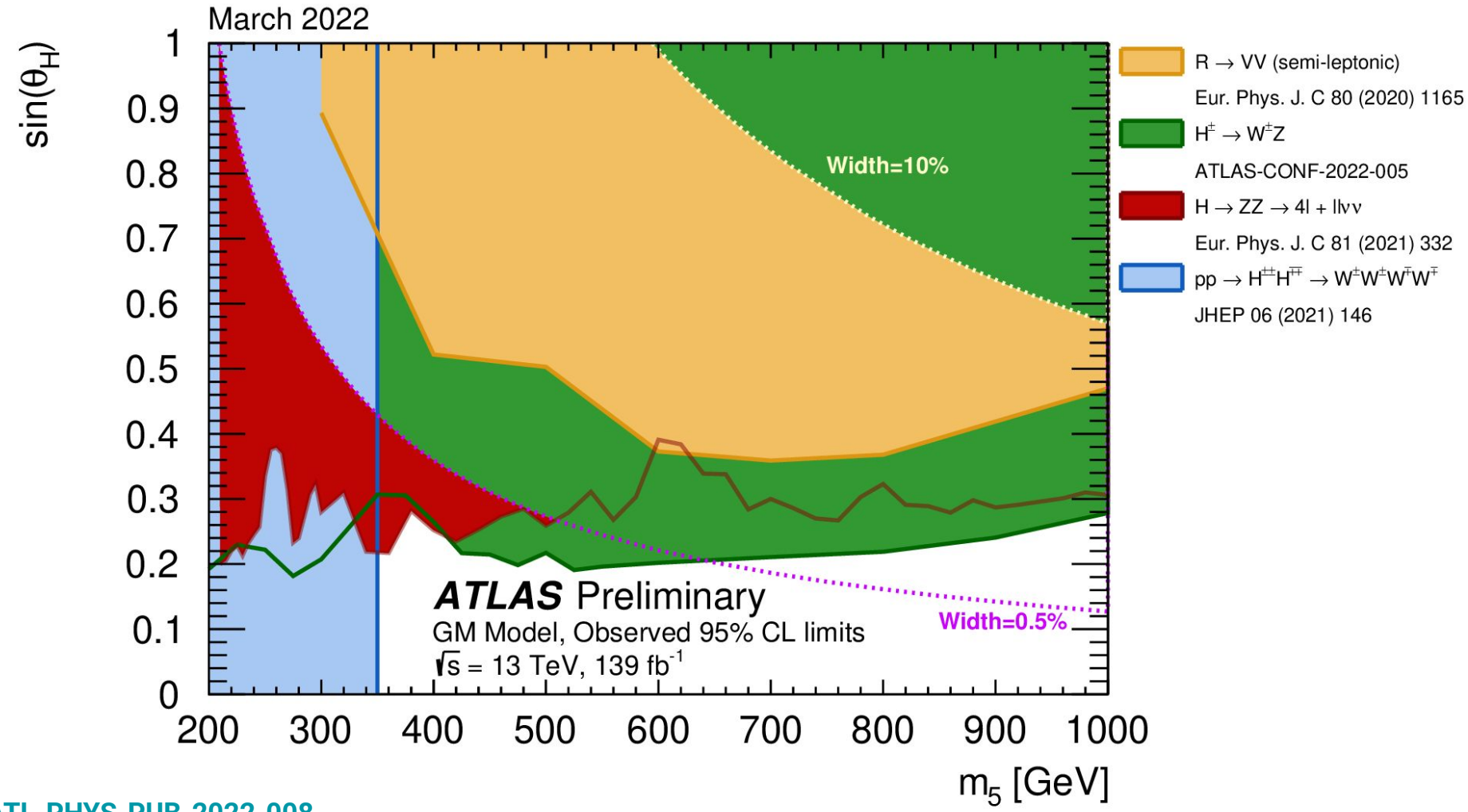






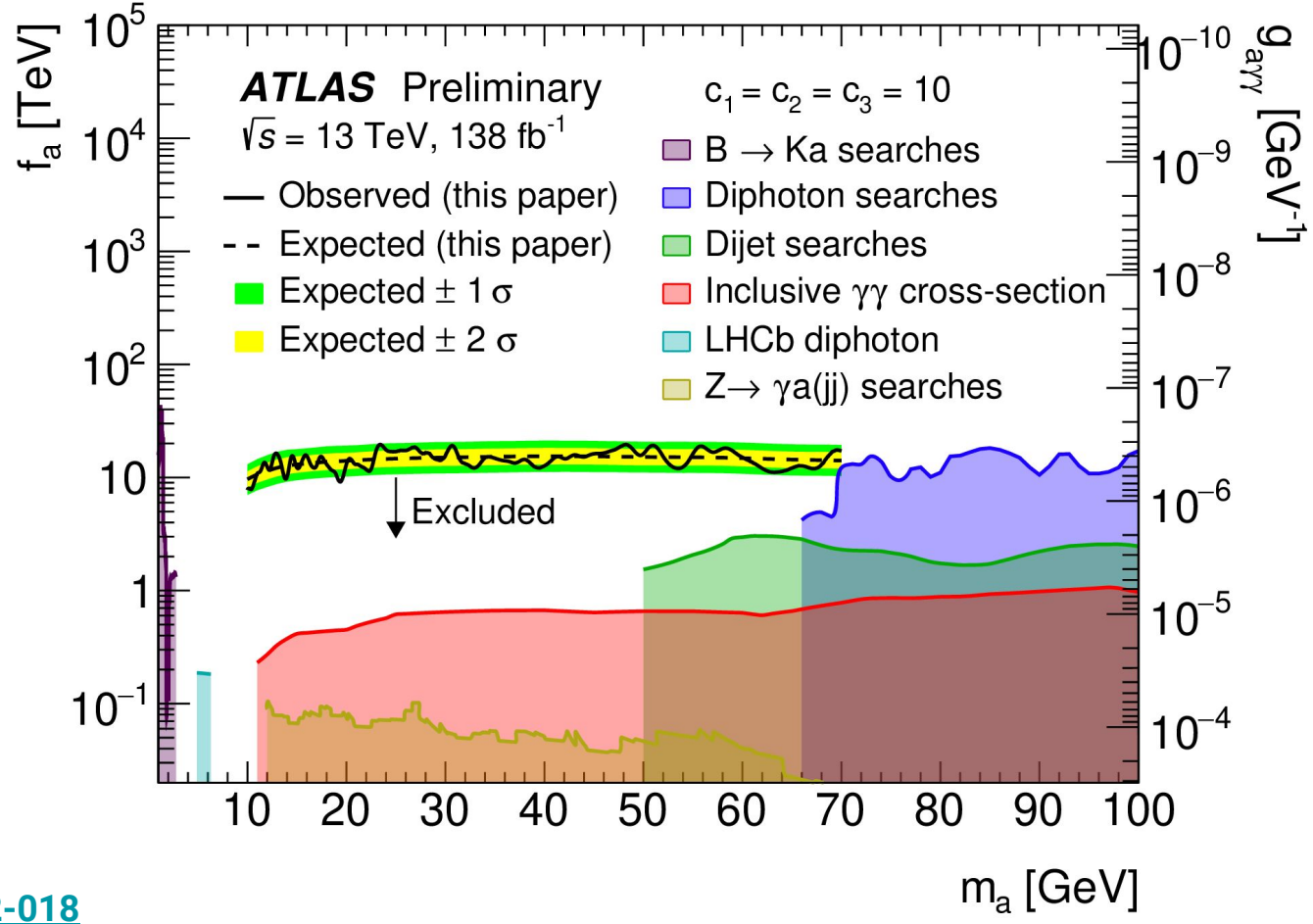
Analysis sees a small excess with a local (global) significance of 3.3σ (1.7σ)

[Phys. Rev. D 105 (2022) 012006]



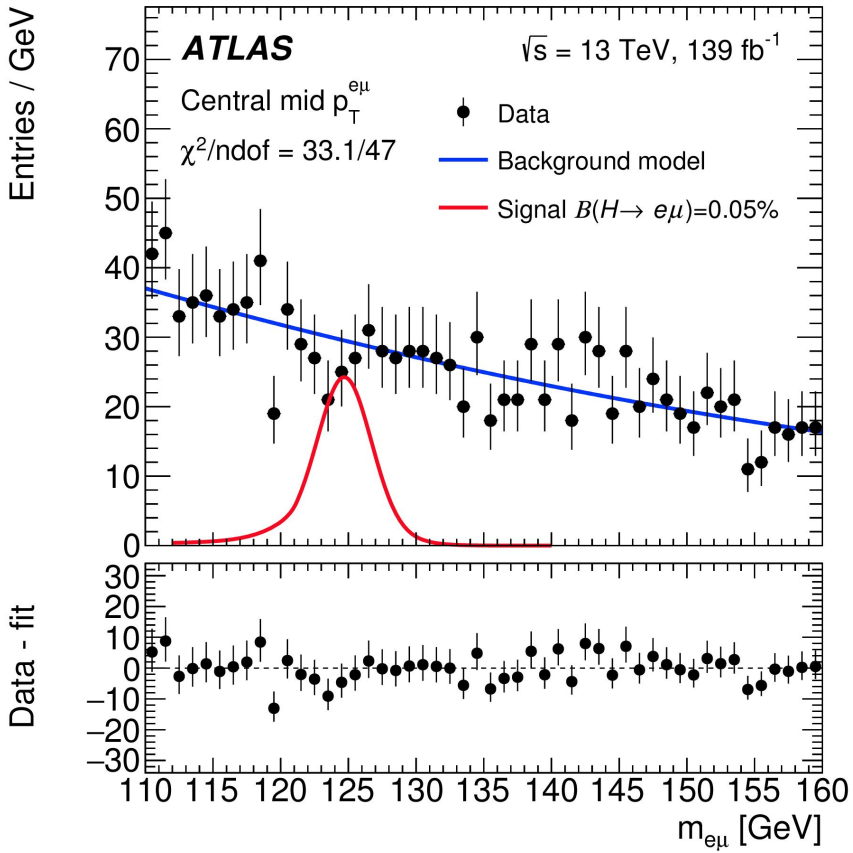
ATL-PHYS-PUB-2022-008

Search for low mass resonances decaying into two photons

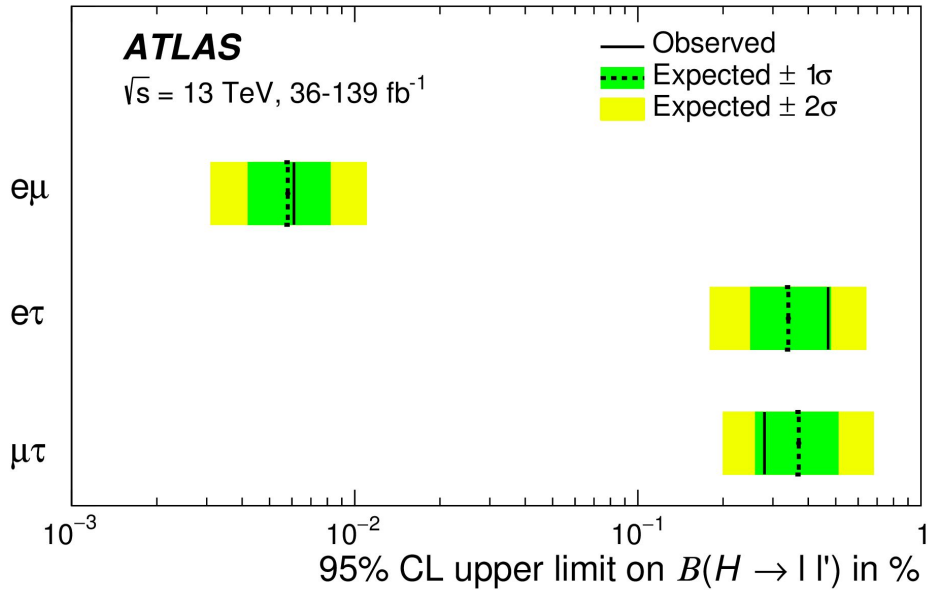


ATLAS-CONF-2022-018

Search for the Higgs boson decays h → eμ

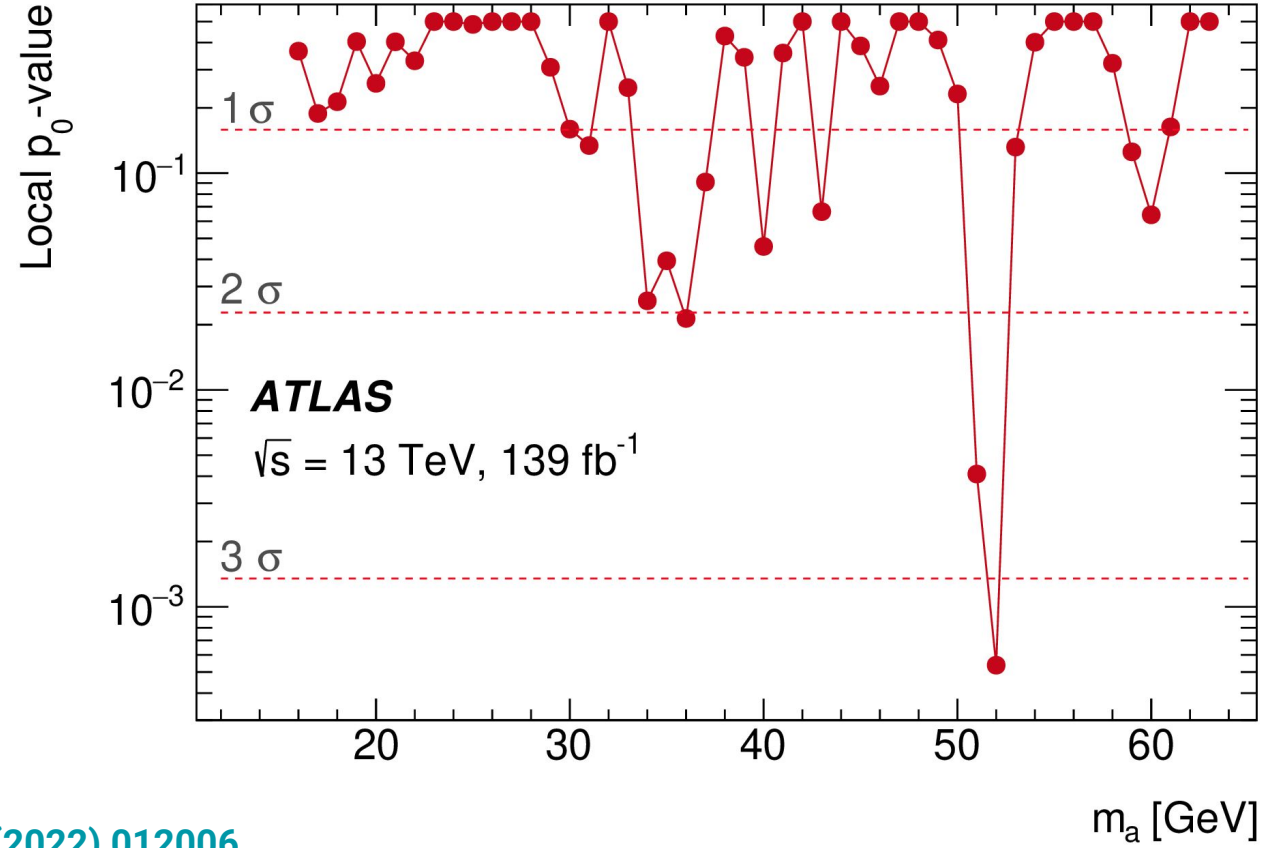


- **Considered production modes:**
  - ggF, VBF, Higgs-Strahlung
- **Predicted by:**
  - Flavour-violating 2HDMs



CERN-EP-2019-184

Search for Higgs boson decays into pseudoscalar particles



Phys. Rev. D 105 (2022) 012006