Searches for additional Higgs bosons at the LHC

Physics at the Terascale

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MAX-PLANCK-INSTITUT FÜR PHYSIK

Motivations for Extended Higgs Sector

- **Why is it crucial to search for an extended Higgs sector ?**
  - Extended Higgs sectors can modify the electroweak phase transition and facilitate baryogenesis.
  - Extended Higgs sectors can enhance vacuum stability.
  - Extended Higgs sectors can provide a dark matter candidate.
  - Extended Higgs sectors can be employed to provide a solution to the strong CP problem ($\Longrightarrow$ axion)
  - Models of new physics beyond the SM often require additional scalar Higgs states. E.g., two Higgs doublets are required in the minimal supersymmetric extension of the SM (MSSM).

Extended scalar sector

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

- **Relevant model parameters**
  - Mixing angle α between neutral states
  - tan β (ratio of vacuum expectation values)

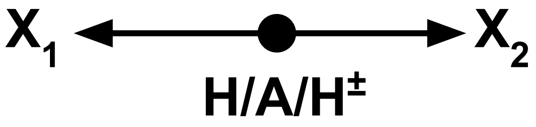
2 Higgs doublets + singlet (i.e. N2HDM) $\xrightarrow{\text{ESB}}$ **h, H, A, $H^\pm$, S**

- **Relevant model parameters**
  - Mixing angle α between neutral states
  - tan β (ratio of VEVs) and v_S (i.e. VEV of singlet)

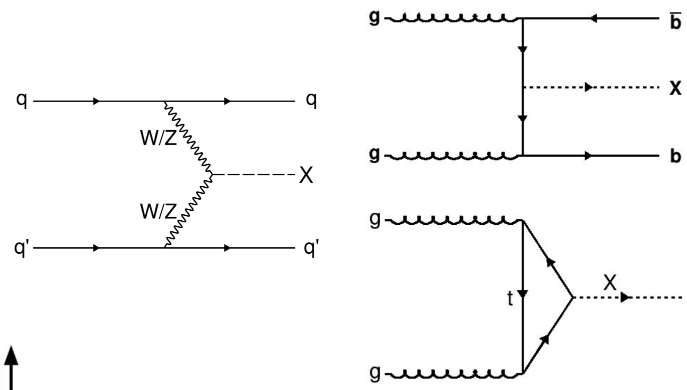
1 Higgs doublet + 2 triplets (GM model) $\xrightarrow{\text{ESB}}$ **h, H, H_3, $H^\pm_3$, H_5, $H^\pm_5$, $H^{\pm\pm}_5$**

- **Relevant model parameters**
  - Mixing angle α between neutral states
  - tan β (ratio of doublet and triplet VEVs)

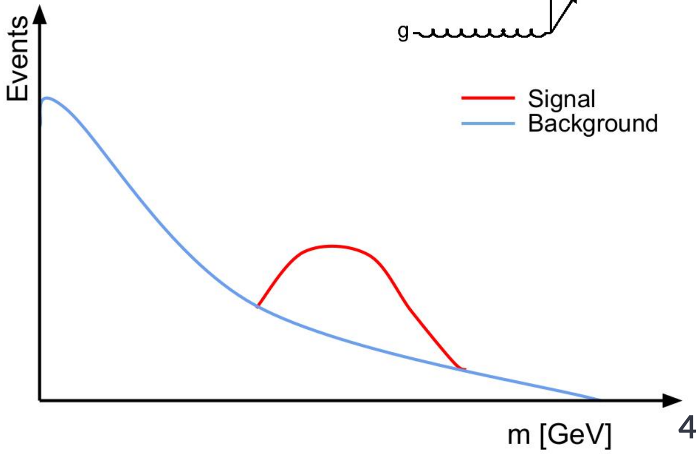
Introduction:



- **Focus: Searches for a heavy Higgs boson H/A/H± decaying into X_1 and X_2 (with X_1/X_2 = γ, Z, W, H, A, h)**
    - Searches are performed for different production modes
    - Targeting diverse sets of final states:
        - Multi-lepton
        - Di-photon
        - Di-tau
        - Lepton + jets
        - b-jets



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



Searches for additional Higgs bosons at the LHC

- **Analysis covered in detail in this presentation:**
  - Search for pseudo scalars in $A \rightarrow Zh$ decays (ATLAS): ATLAS-CONF-2020-043
  - Search for a heavy Higgs boson decaying to $\gamma\gamma$ (ATLAS): ATLAS-CONF-2020-037
  - Search for heavy charged Higgs bosons $H^+ \rightarrow tb$ (ATLAS): JHEP 06 (2021:) 145
  - Searches for a light charged Higgs bosons decaying via $H^+ \rightarrow cb$ (ATLAS): ATLAS-CONF-2021-037
  - Search for fermiophobic charged Higgs bosons (CMS): arXiv:2104.04762
  - Search for doubly and singly charged Higgs bosons (ATLAS): JHEP 06 (2021) 146

- **Further analysis:**
  - Search for a heavy Higgs boson decaying to WW (CMS): JHEP 03 (2020) 034
  - Search for pseudo scalars in $A \rightarrow Zh$ decays (CMS): JHEP 03 (2020) 065
  - Search for new neutral Higgs bosons decaying via $H \rightarrow ZA$ or $A \rightarrow ZH$ (CMS): *JHEP 03 (2020) 055*
  - Search for a heavy Higgs boson in $A \rightarrow ZH$ decays (ATLAS): HDBS-2018-13
  - Search for a new scalar resonance decaying to ZZ (CMS): JHEP 06 (2018) 127
  - Search for $h\gamma$ resonances (CMS): PRL 122 (2019) 081804
  - Search for $h\gamma$ resonances (ATLAS): arXiv:2008.05928
  - Search for high mass resonances decaying via $X \rightarrow WW \rightarrow l\nu l\nu$ (ATLAS): Eur. Phys. J. C 78 (2018) 24
  - Search for a dark Higgs boson decaying into WW or ZZ (ATLAS): arXiv:2010.06548
  - Search for resonances in $X \rightarrow aa \rightarrow bbbb$ decays (CMS): CMS-PAS-B2G-20-003
  - Searches for a light charged Higgs bosons decaying via $H^+ \rightarrow W^+A$ (ATLAS): ATLAS-CONF-2021-047
  - Search for a heavy Higgs boson decaying to ZZ (ATLAS): arXiv2009.14791

Search for pseudo scalars in A → Zh decays:

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

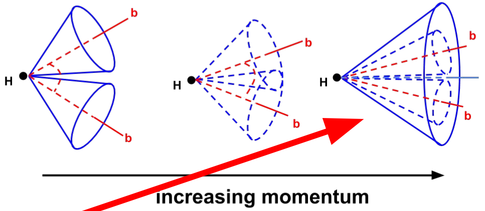
$$m_{\mathrm{T},Vh} = \sqrt{\left(E_{h,\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}}\right)^2 - \left(\vec{p}_{h,\mathrm{T}} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}}\right)^2}$$

- **Dominant uncertainties:**
  - Modelling of backgrounds (top bkg. ME +PS)
  - Large-R jets (mass resolution)

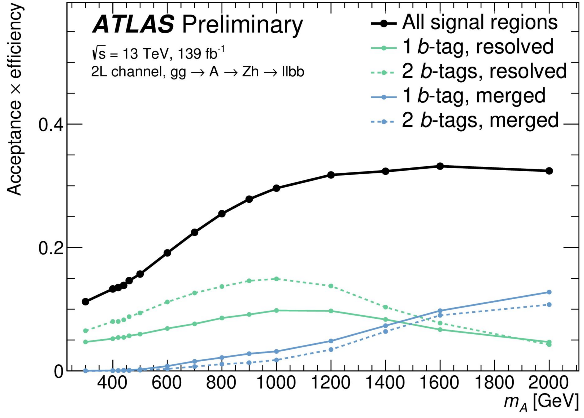
Resolved: use two small-R jets

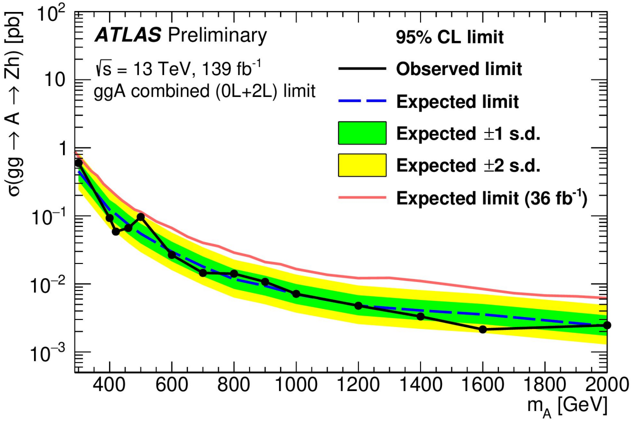
Merged: use a large-R jet to reconstruct Higgs bosons with around p_T > 250GeV

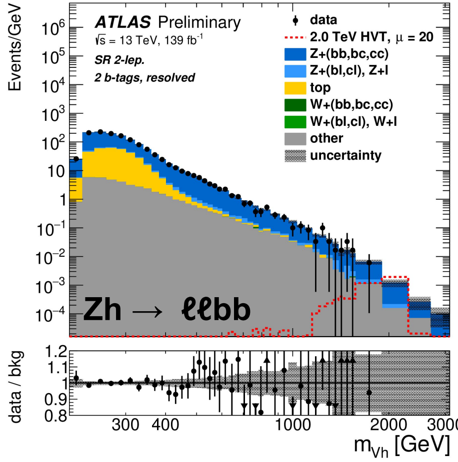
for m_h = 125 GeV



$$\Delta R \approx \frac{2m}{p_{\mathrm{T}}}$$







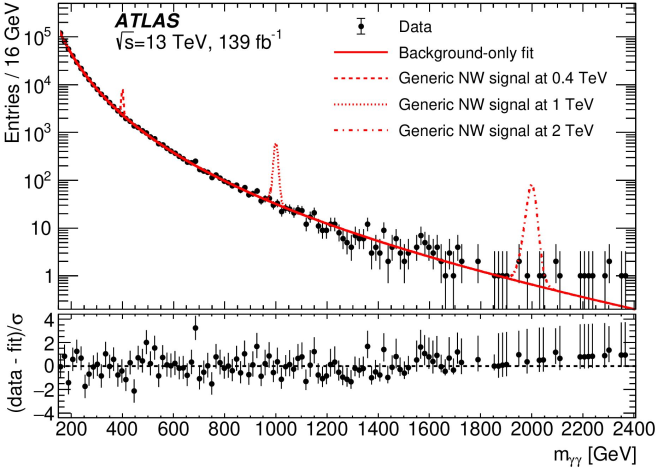
ATLAS-CONF-2020-043

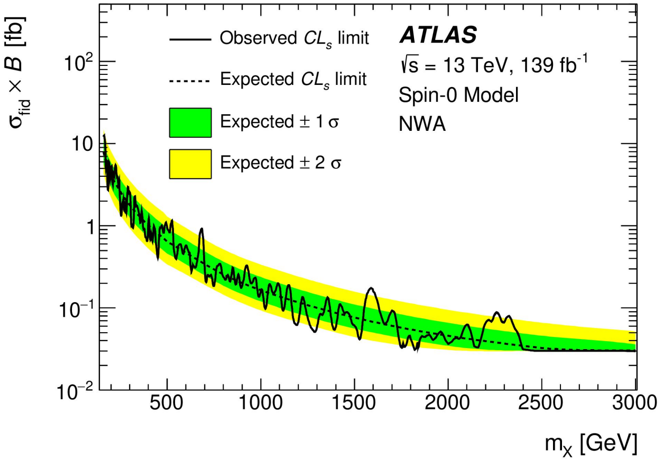
Search for a heavy resonance decaying to γγ:

- **Search for spin-0 (and spin-2) γγ resonance in $m_{\gamma\gamma}$ spectrum**
- **Analysis strategy:**
  - Signal is modelled using a double-sided Crystal Ball function (for NW + LW) convolved with a relativistic Breit-Wigner (only for LW) form
  - Background (γγ, γj, jj) sum is estimated via fit to data:

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

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



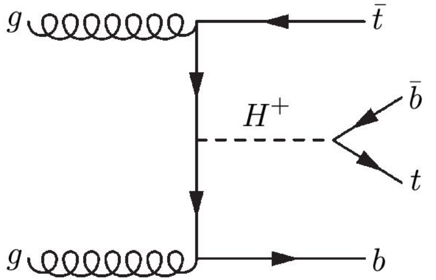


Largest local (global) deviation wrt SM expectations was found to be 3.3σ (1.3σ) for a mass around 680 GeV

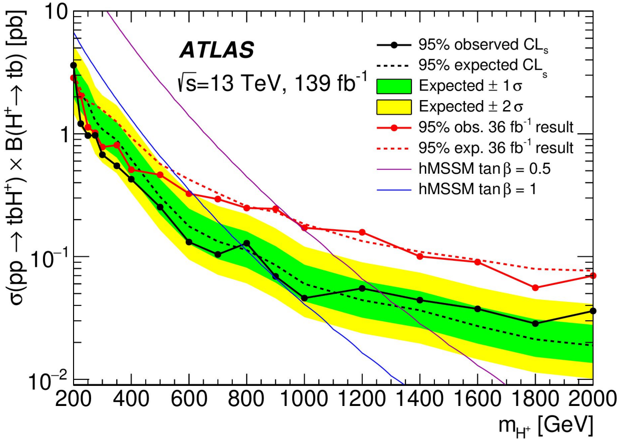
[Phys. Lett. B 822 (2021) 136651]

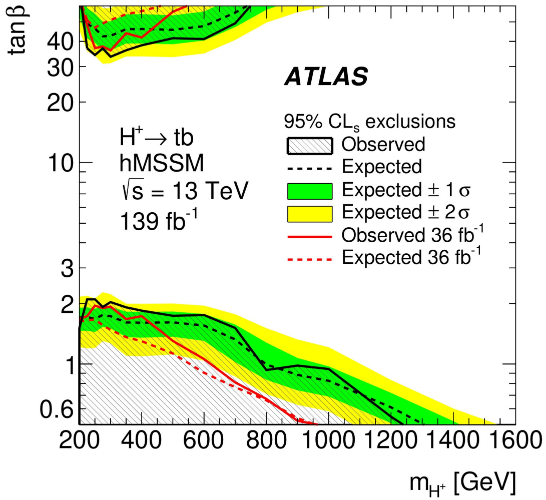
Search for heavy charged Higgs bosons:

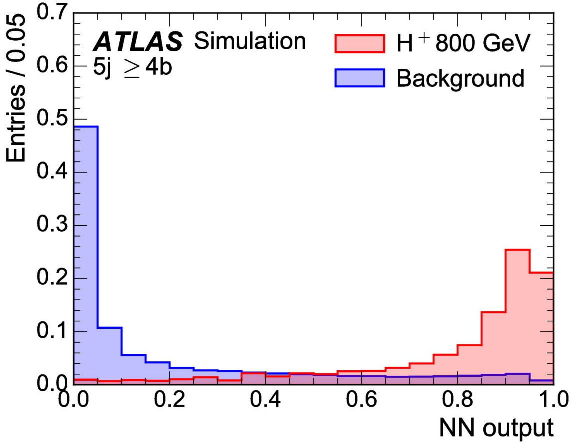
- **Search for heavy charged Higgs bosons decaying via: $H^+ \rightarrow tb$ ($m_H > m_{top} + m_b$)**
  - **Results in complicated final states: lνjjbbbb, lνlνbbbb**
  - **Train a neural network** for each mass point $m_{H+} \in$ [0.2 TeV, 2TeV]
    - Separate NNs for different jet/b-jet multiplicities
    - NN discriminants are used as input to LLH fit



- **Uncertainties are dominated by tt+HF modelling and b-tagging**



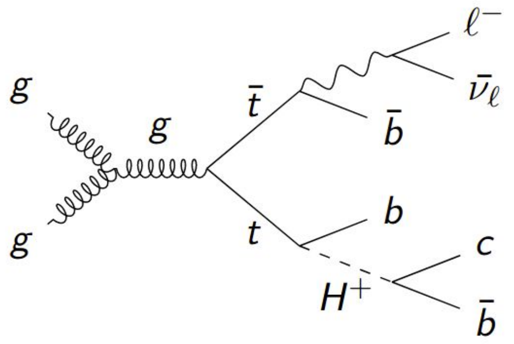


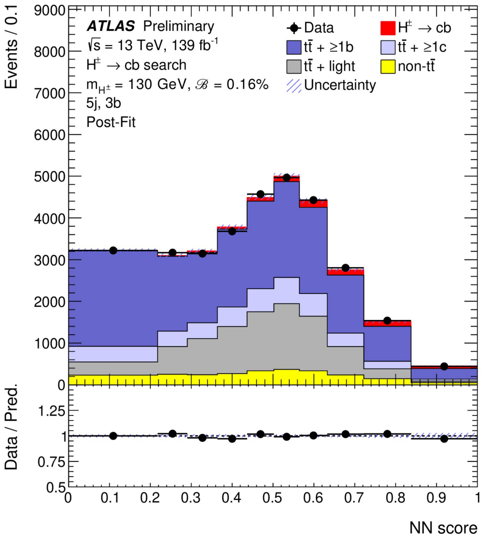


[JHEP 06 (2021) 145](https://doi.org/)

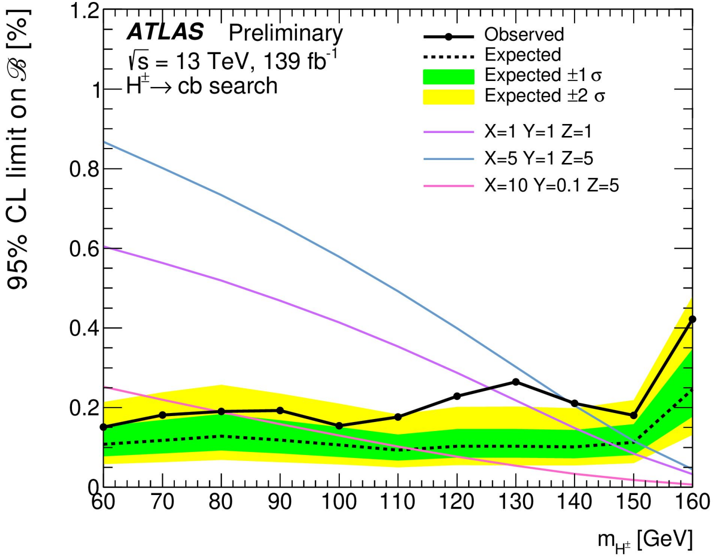
Searches for a light charged Higgs bosons decaying via $H^+ \to cb$

- **Search for ℓνcbbb (ℓ = μ, e) final states**
- **Analysis strategy:**
  - Simultaneous fit of NN response distributions in various jet and b-tag multiplicity regions
- Motivated by **3HDM**
- **Dominant systematic uncertainties:**
  - Background modelling





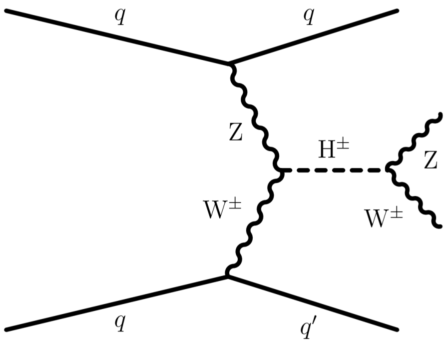
Largest excess around a mass of 130 GeV corresponding to a local (global) significance of around 3σ (2σ)

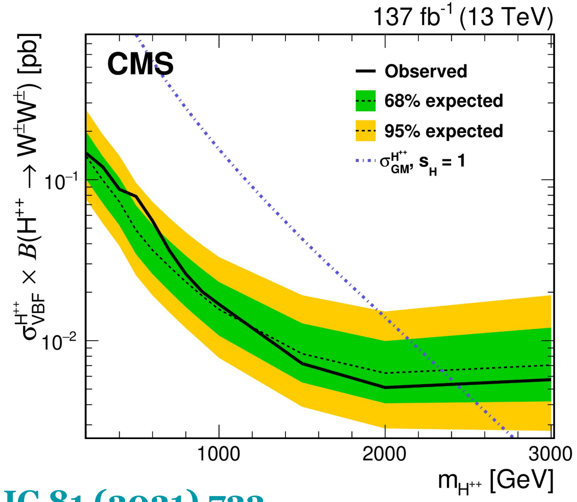


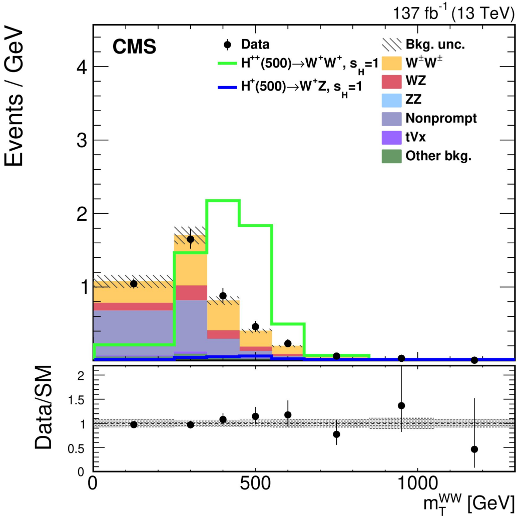
ATLAS-CONF-2021-037

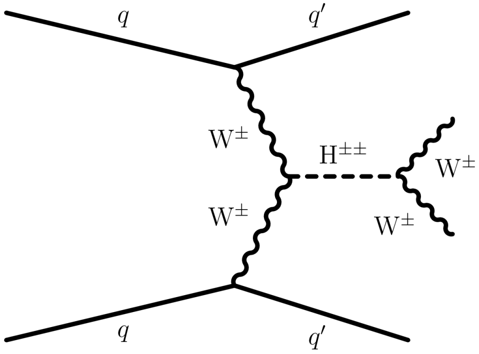
Search for fermiophobic charged Higgs bosons:

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







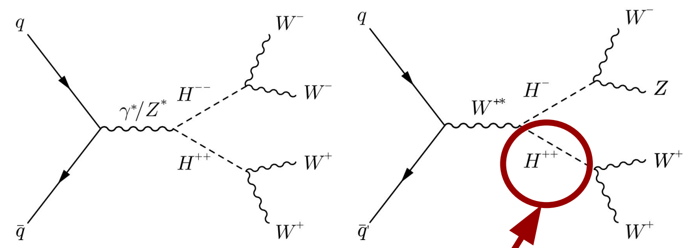


Predicted in e.g. Higgs triplet models

EPJC 81 (2021) 723

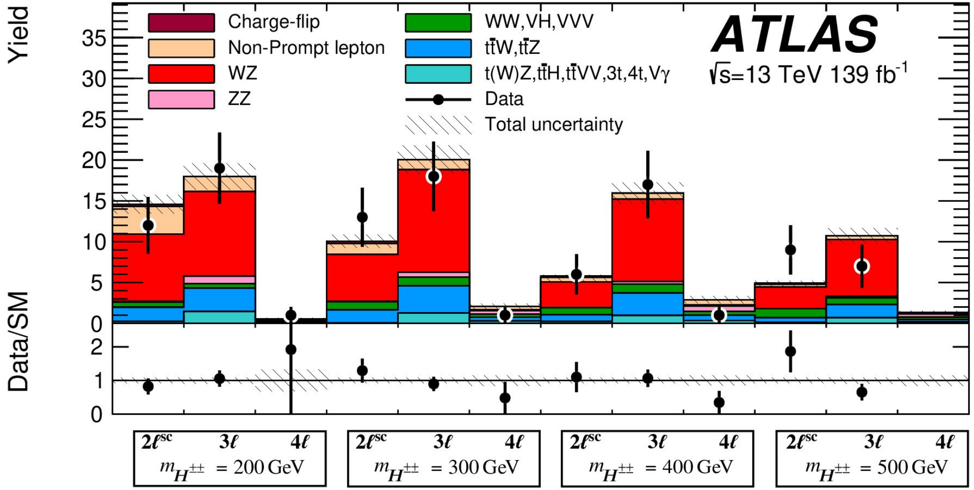
Search for doubly and singly charged Higgs bosons:

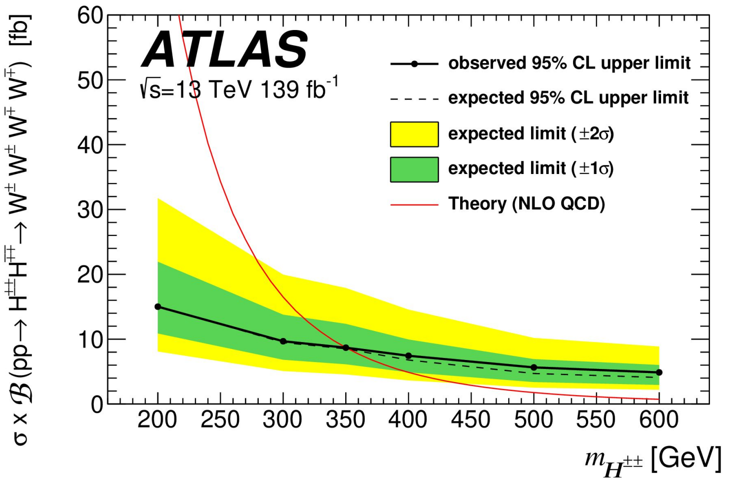
- **Probe multi-lepton final states ($2\ell^{SC}$, 3ℓ, 4ℓ)**
- **Analysis strategy:**
  - Define signal regions (angular distances, invariant masses)
  - Probe for excess of observed signal region yields
  - Simultaneous fit of the three signal regions
- **Dominant systematic uncertainties:**
  - Non-prompt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



JHEP 06 (2021) 146

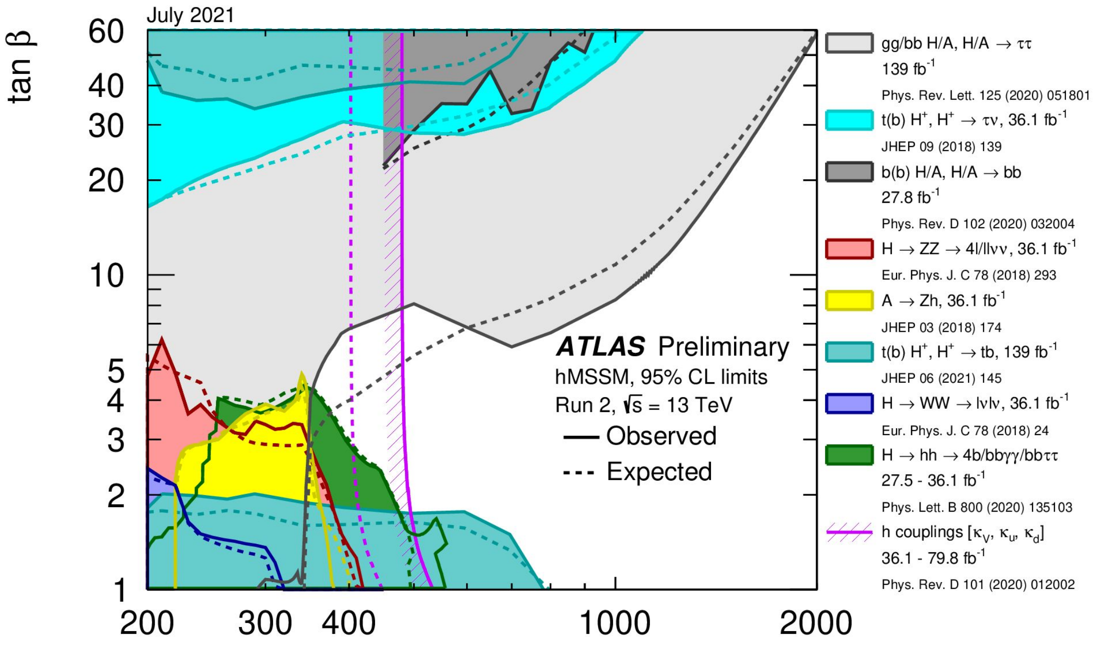
Predicted in Higgs triplet models (needed for e.g. type-II seesaw mechanism)



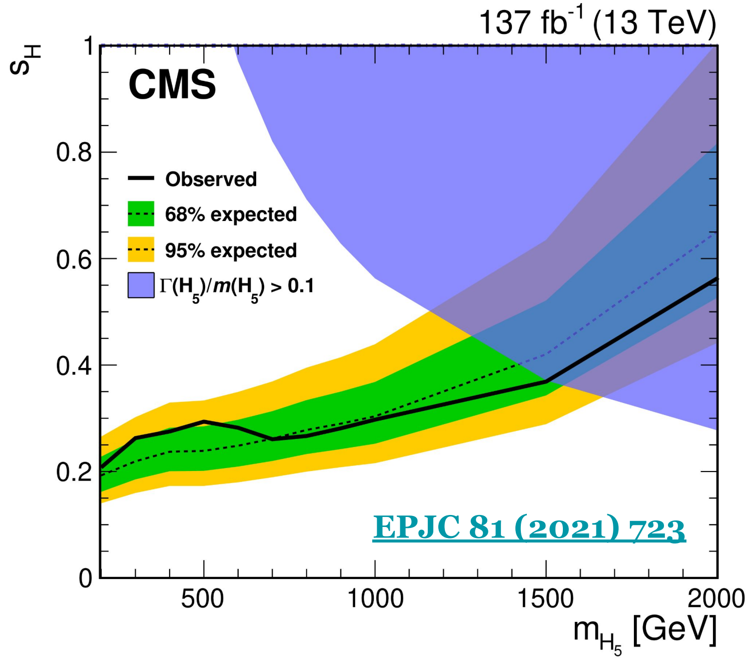


Interpretations:

- **Model independent limits are re-interpreted in the context of e.g. the 2HDM (specifically the MSSM) or Higgs triplet models (specifically the Georgi-Machacek)**



ATL-PHYS-PUB-2021-030



EPJC 81 (2021) 723

Concluding remarks

- **Essential to search for an extended Higgs sector !!!**
- CMS and ATLAS have recently published several exciting experimental results on searches for additional Higgs bosons
  - Presented only a few highlights of available results.
    - Additional results can be found via the **ATLAS** and **CMS** publication pages
  - No significant hint for physics beyond the SM has been observed so far
  - Many results based on the full Run-2 data set are expected in the next month/years

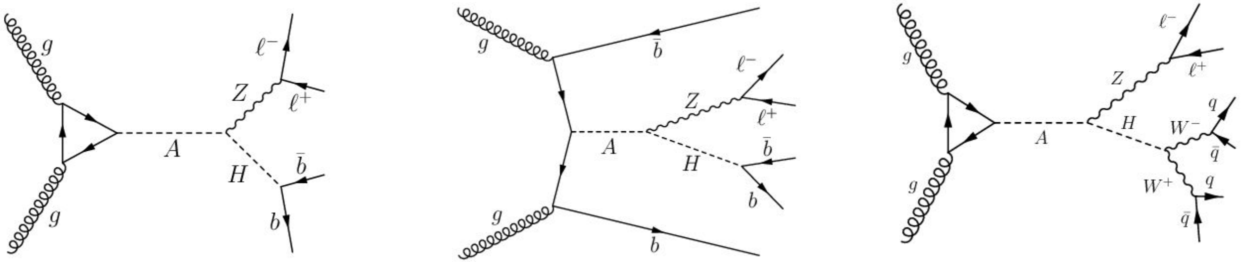
Back-up

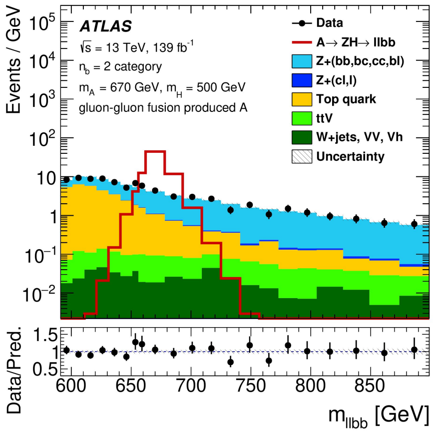
2HDM

- The 2-Higgs Doublet Model (2HDM) with 2 complex Higgs doublets is (together with the singlet extension) the simplest possible extension
    - **Motivated by e.g. supersymmetric model**
    - **Introduces additional sources for explicit or spontaneous CP violation**
- The scalar potential of the two Higgs doublets Φ_1 and Φ_2 can have CP-conserving, CP-violating or charge-violating minima
- **Distinguish several 2HDM scenarios based on how leptons and quarks couple to the doublets**

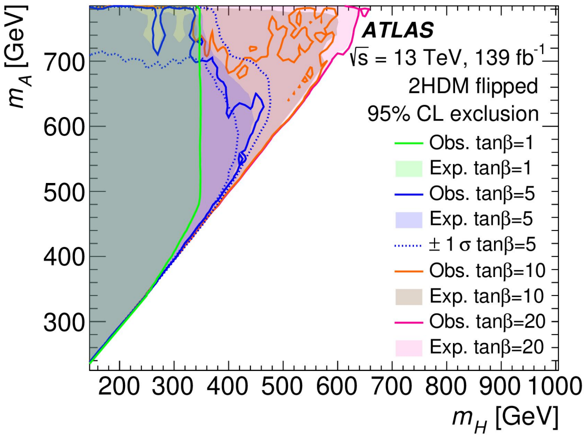
Model:	Type I	Type II	Type X	Type Y
Φ_1	-	d, ℓ	ℓ	d
Φ_2	u,d,ℓ	u	u,d	u, ℓ

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





- **Search for a new scalar decaying via A → ZH (m_H>125 GeV)**
  - Probe gg → A and bbA production modes
  - Consider H → bb (for gg → A and bbA) and H → WW (for gg → A) decays leading to ℓℓbb and ℓℓqqqq final states (with ℓ = μ,e)



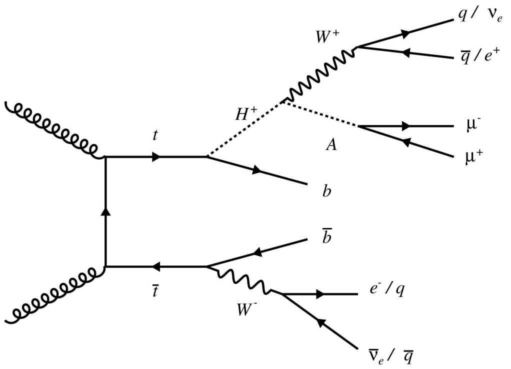
Largest local (global) deviation wrt SM expectations was found to be 3.1σ (1.3 σ) for (m_A,m_H)=(610,290) GeV

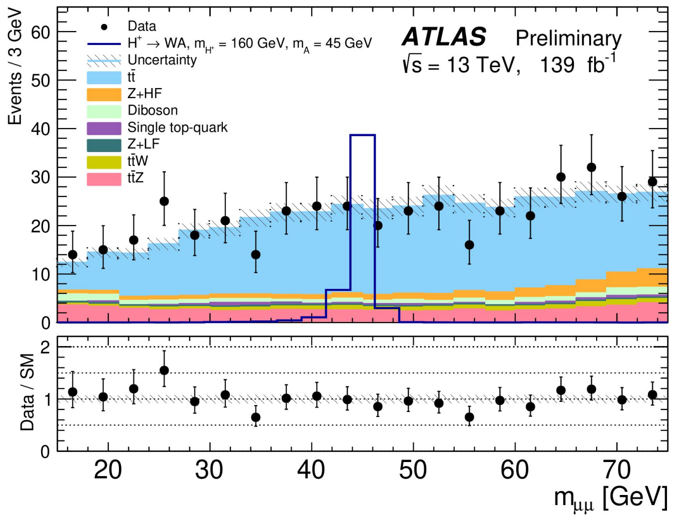
- **Analysis strategy:**
  - Signal parameterization:
    - ExpGaussExp (for ℓℓbb)
    - Double-Gaussian Crystal Ball (for ℓℓbbbb and ℓℓqqqq)
  - Fit m_A distribution in windows around m_H
- **Dominant syst. uncertainties:**
  - Data statistics
  - JES/JER

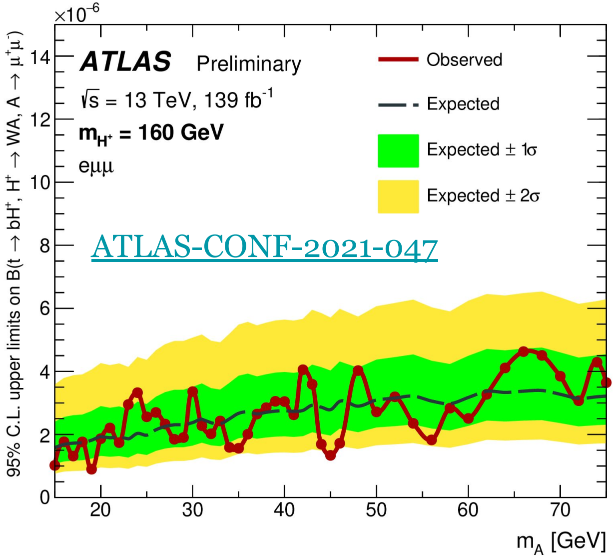
Eur. Phys. J. C. 81 (2021) 396

Searches for a light charged Higgs bosons decaying via $H^+ \rightarrow W^+A$

- **Search for eνμμqqbb final states**
- **Analysis strategy:**
  - Simultaneous fit of $m_{\mu\mu}$ distribution in SRs and CRs for different charged Higgs mass hypothesis
- **Dominant systematic uncertainties:**
  - Modelling of top quark backgrounds



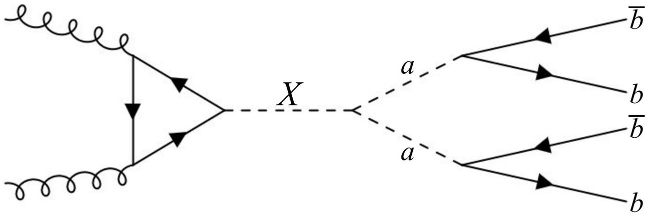




ATLAS-CONF-2021-047

Search for resonances in X → aa→ bbbb decays:

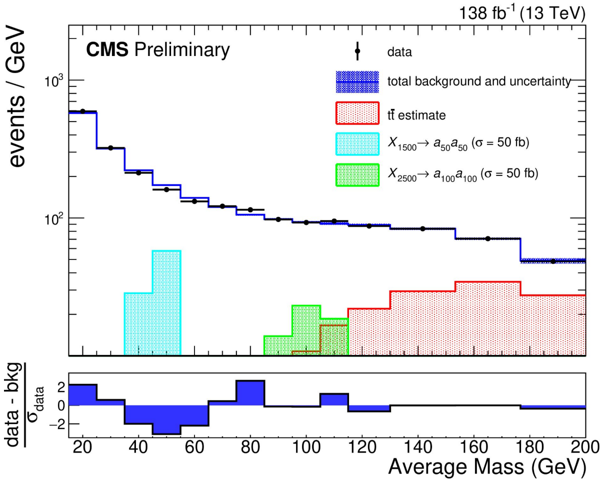
- **Probe merged bbbb final states**
- **Analysis strategy:**
  - Reconstruct a→ bb decays using large-R jets and **double b-tagging** (via the so-called D^{bb} score)
  - Search for localized excess in the two-dimensional distributions of the **average jet mass** and **dijet mass**
  - QCD background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

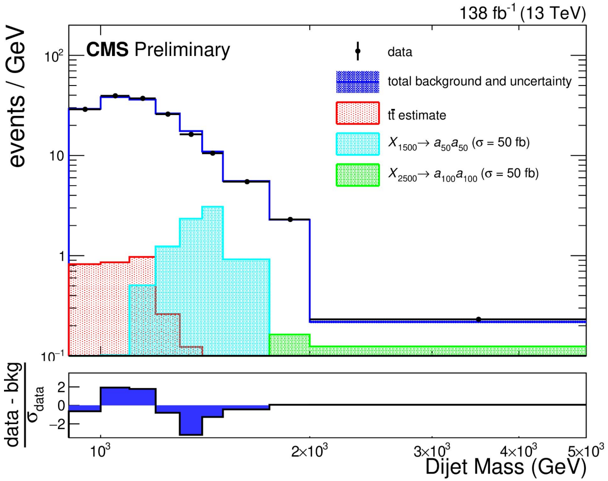


CMS-PAS-B2G-20-003

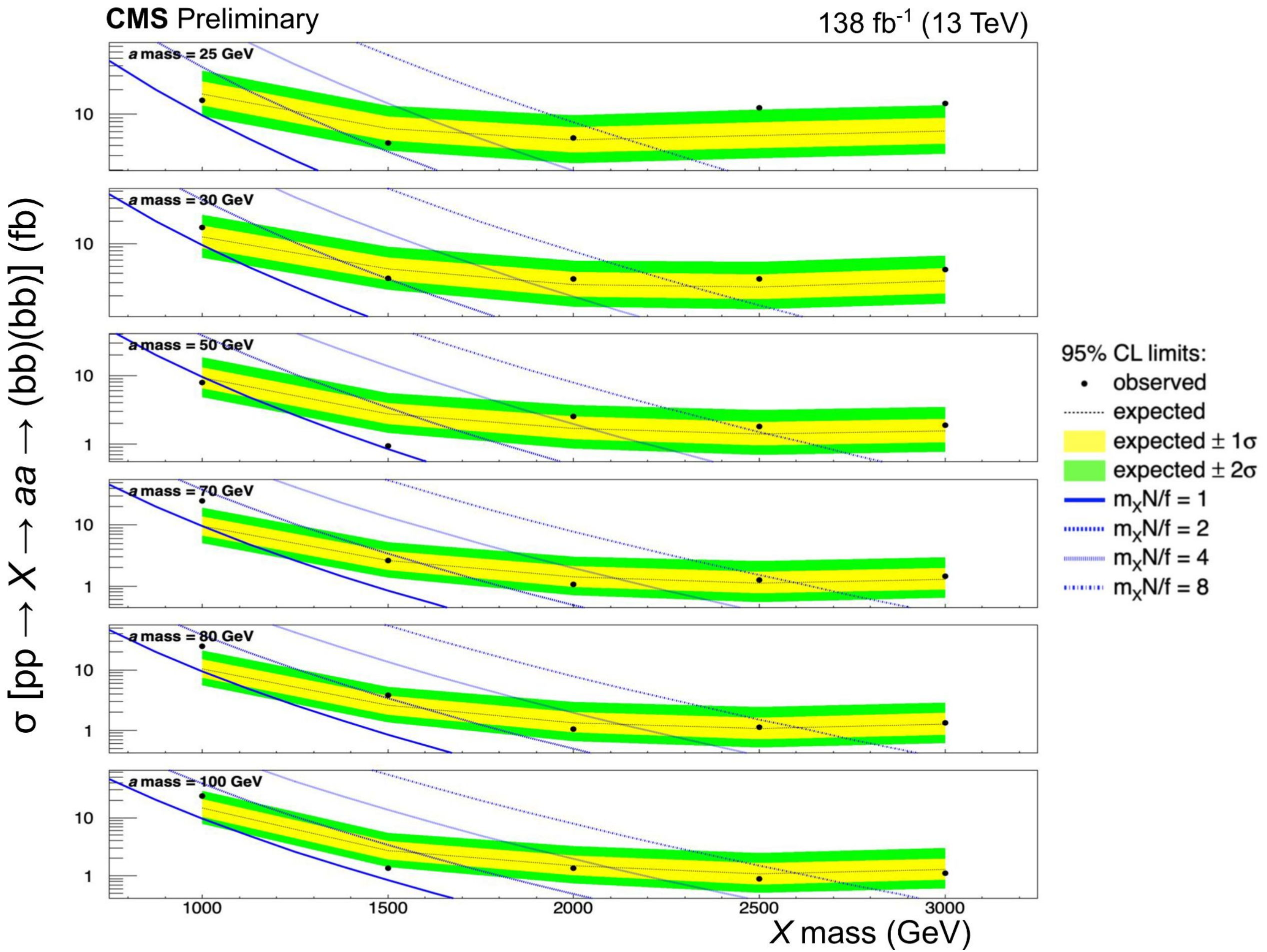
- **Use several SRs and CRs**
  - Definition based on::
    - Jet masses asymmetry
    - Pseudorapidity gap
    - D^{bb} score

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





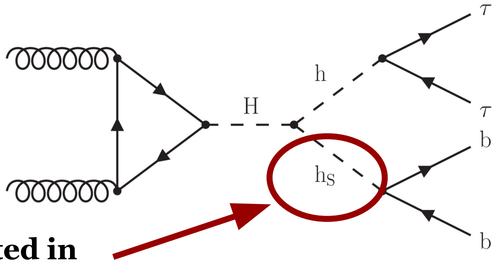
Search for resonances in X → aa→ bbbb decays:



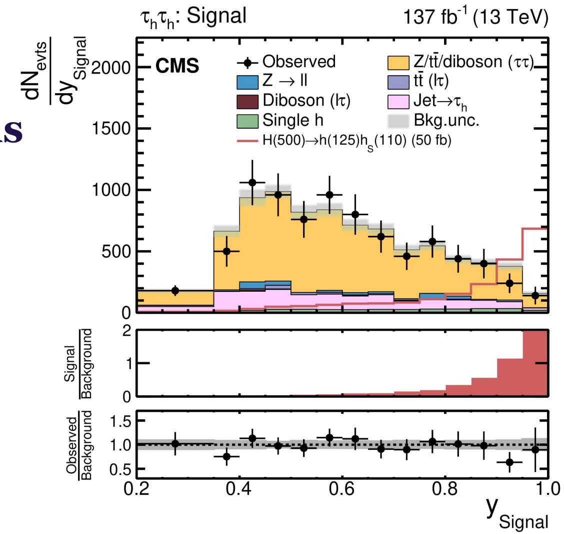
CMS-PAS-B2G-20-003

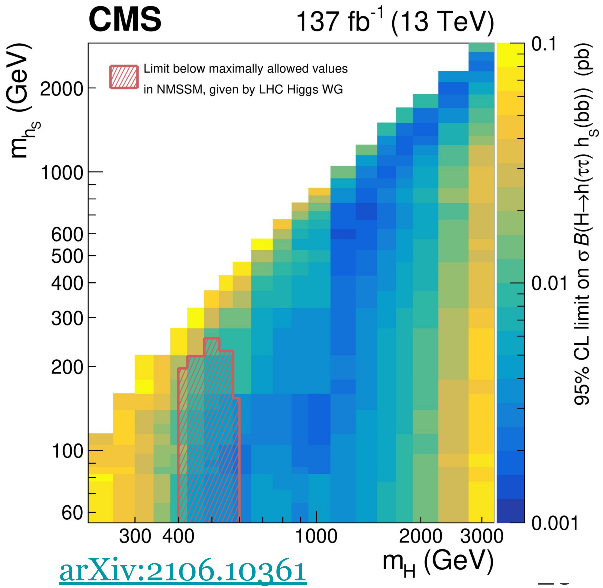
Search for resonances in H→ hh_S→ bbττ decays:

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



Predicted in e.g. NMSSM





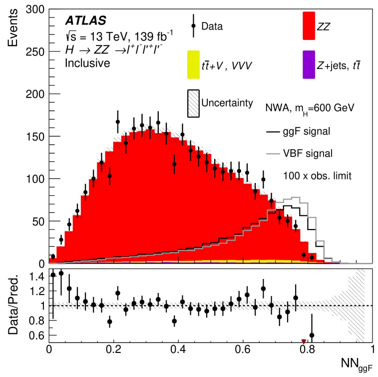
arXiv:2106.10361

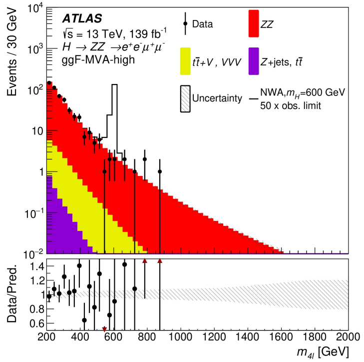
Search for a heavy Higgs boson decaying to ZZ:

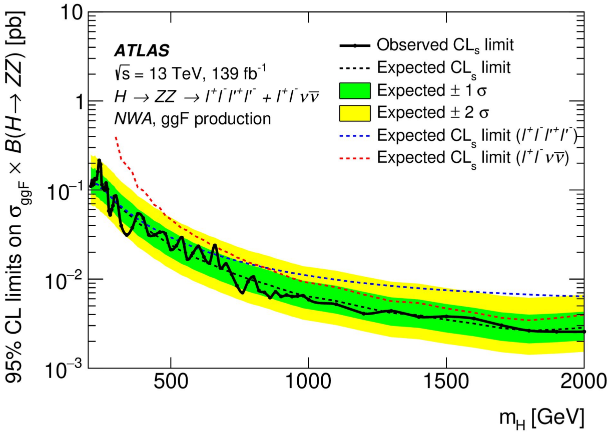
- **Probe ℓℓℓℓ and ℓℓνν final states (with ℓ = μ,e):**
  - Probe $m_{\ell\ell\ell\ell}$ and m_T spectra for signal hypotheses in range between 240 GeV and 2 TeV
- **Analysis strategy:**
  - Use two sets of neural networks (rNN + MLP) to classify 4ℓ events:
    - ggF: 4-vectors of leptons + kinematics of ℓℓℓℓ-system
    - VBF: 4-vectors of leptons and jets + ℓℓℓℓ-system
  - ℓℓνν events are classified via rectangular cuts
  - Fit ggF (VBF) contribution and floating VBF (ggF)
    - Combined fit using $m_{\ell\ell\ell\ell}$ and m_T distributions
    - Interference effects (between H, h and continuum) are taken into account
- **Dominant systematics:**
  - Systematics are negligible wrt statistical uncertainty (~50%)

Eur. Phys. J. C 81 (2021) 332

$$m_T \equiv \sqrt{\left[\sqrt{m_Z^2 + \left(p_T^{\ell\ell}\right)^2} + \sqrt{m_Z^2 + \left(E_T^{\text{miss}}\right)^2}\right]^2 - \left|\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{\text{miss}}\right|^2}$$





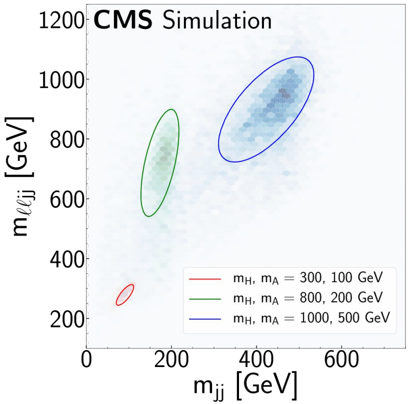


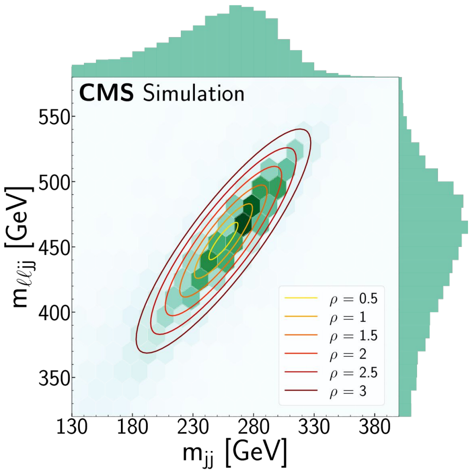
Search for new neutral Higgs bosons decaying via H→ZA or A → ZH:

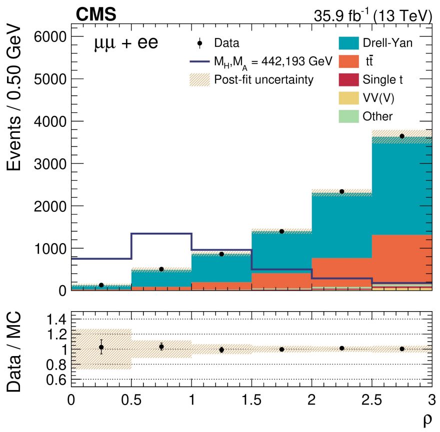
for $m_H \neq 125$ GeV

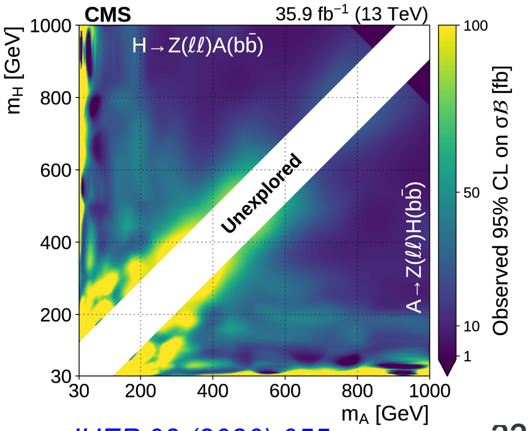
- **Probe ℓℓbb (ℓ = μ,e) final states**
- **Analysis strategy:**
  - Probe m_{jj} and $m_{\ell\ell bb}$ distributions for bumps within elliptical SRs
    - Size of ellipsoids depend on resonance masses (due to JER)
  - Transform 2D mass distribution into 1D distribution ρ:
    - Value of ρ depends on distance to the peak position of the 2D mass distribution
  - ML fit is performed using the distribution of ρ in ee + μμ SRs as well as in eμ + μe CRs as input
- **Dominant systematics:**
  - Modelling of the top quark, Z + jets and diboson backgrounds
    - In particular QCD scale uncertainties (~10%)

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









JHEP 03 (2020) 055

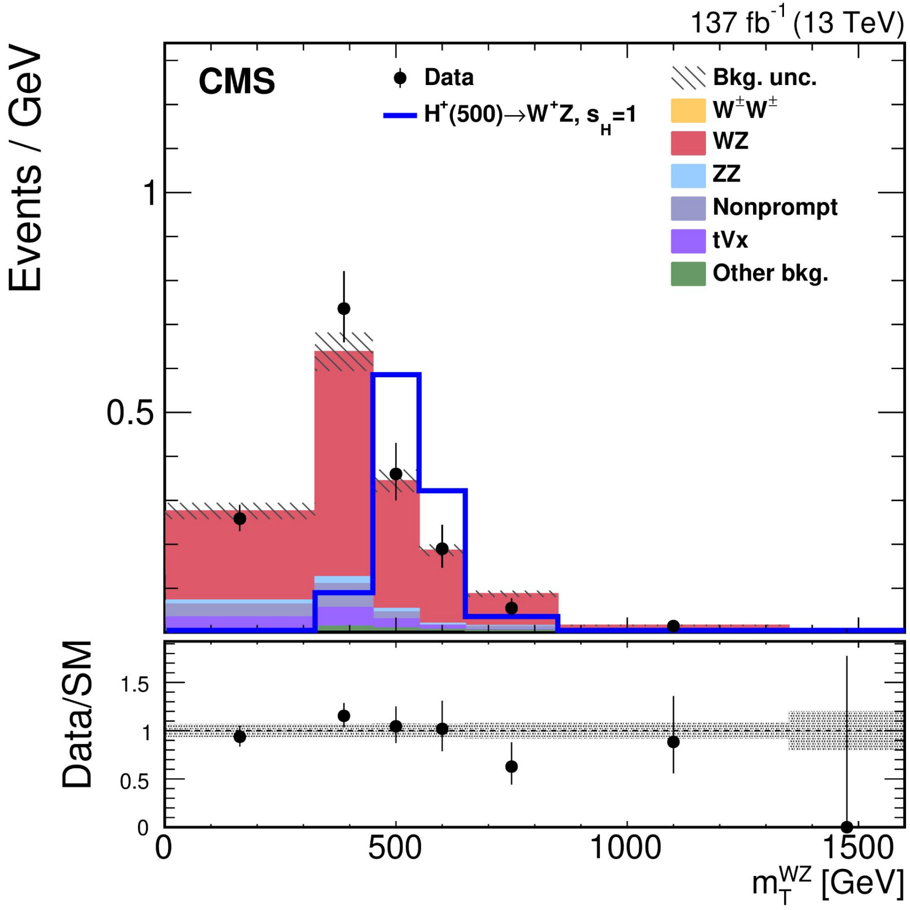
Search for leptophobic charged Higgs bosons:

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

arXiv:2104.04762

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

Search for leptophobic charged Higgs bosons:



arXiv:2104.04762

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

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

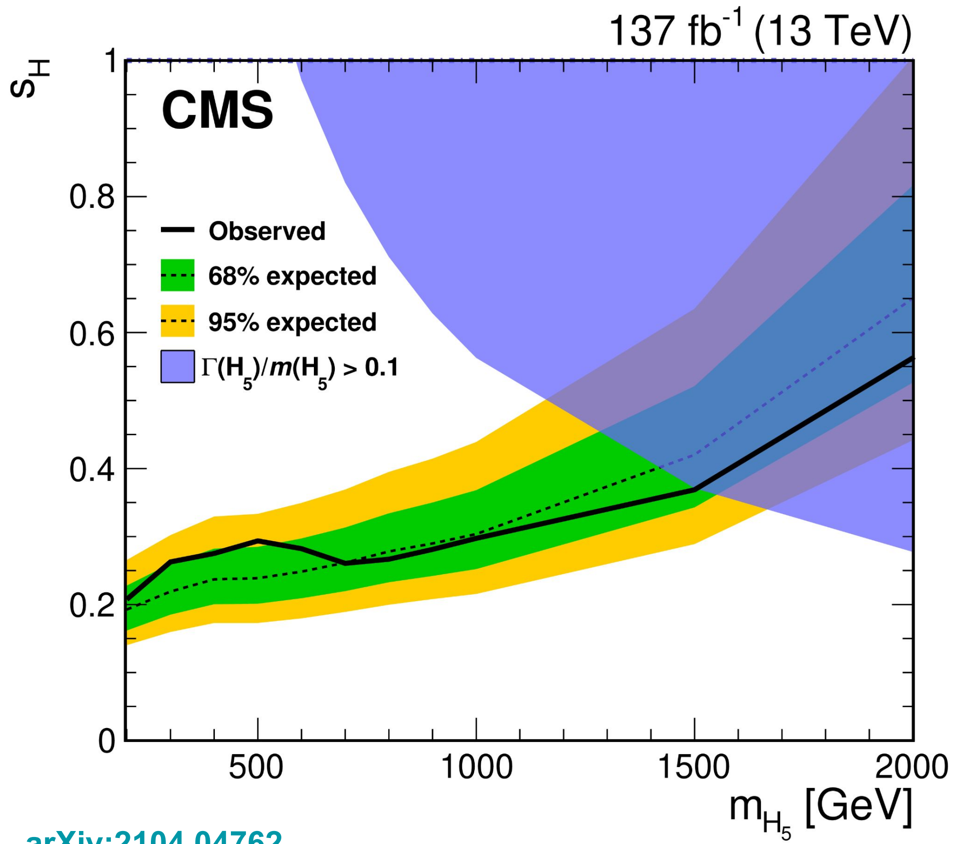
Search for leptophobic charged Higgs bosons:

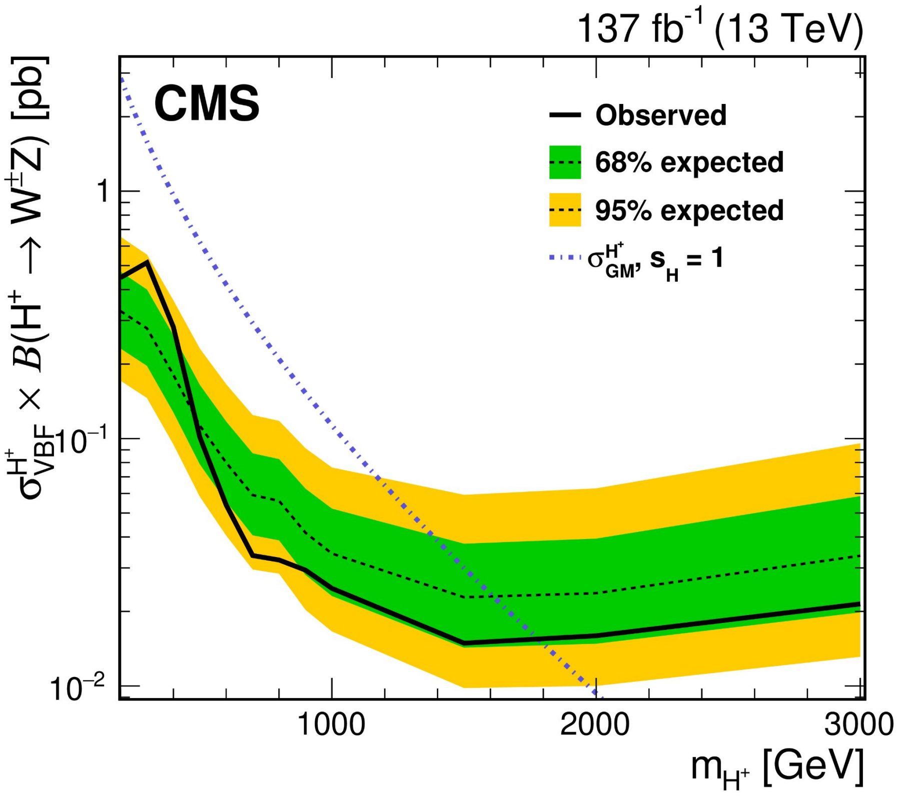
Expected signal and background yields from various SM processes and observed data events in all regions used in the analysis. The expected background yields are shown with their normalisations from the simultaneous fit for the background-only hypothesis

arXiv:2104.04762

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

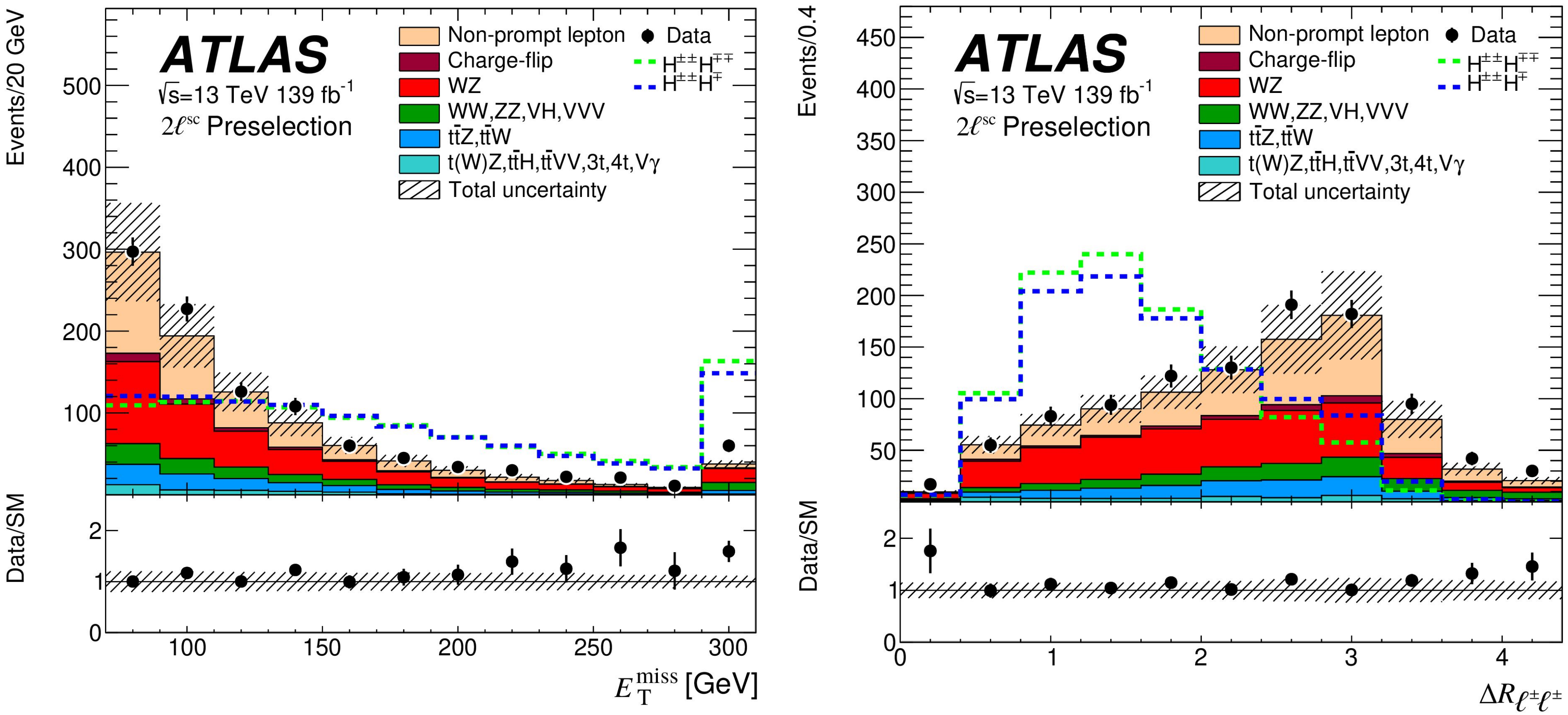
Search for leptophobic charged Higgs bosons:





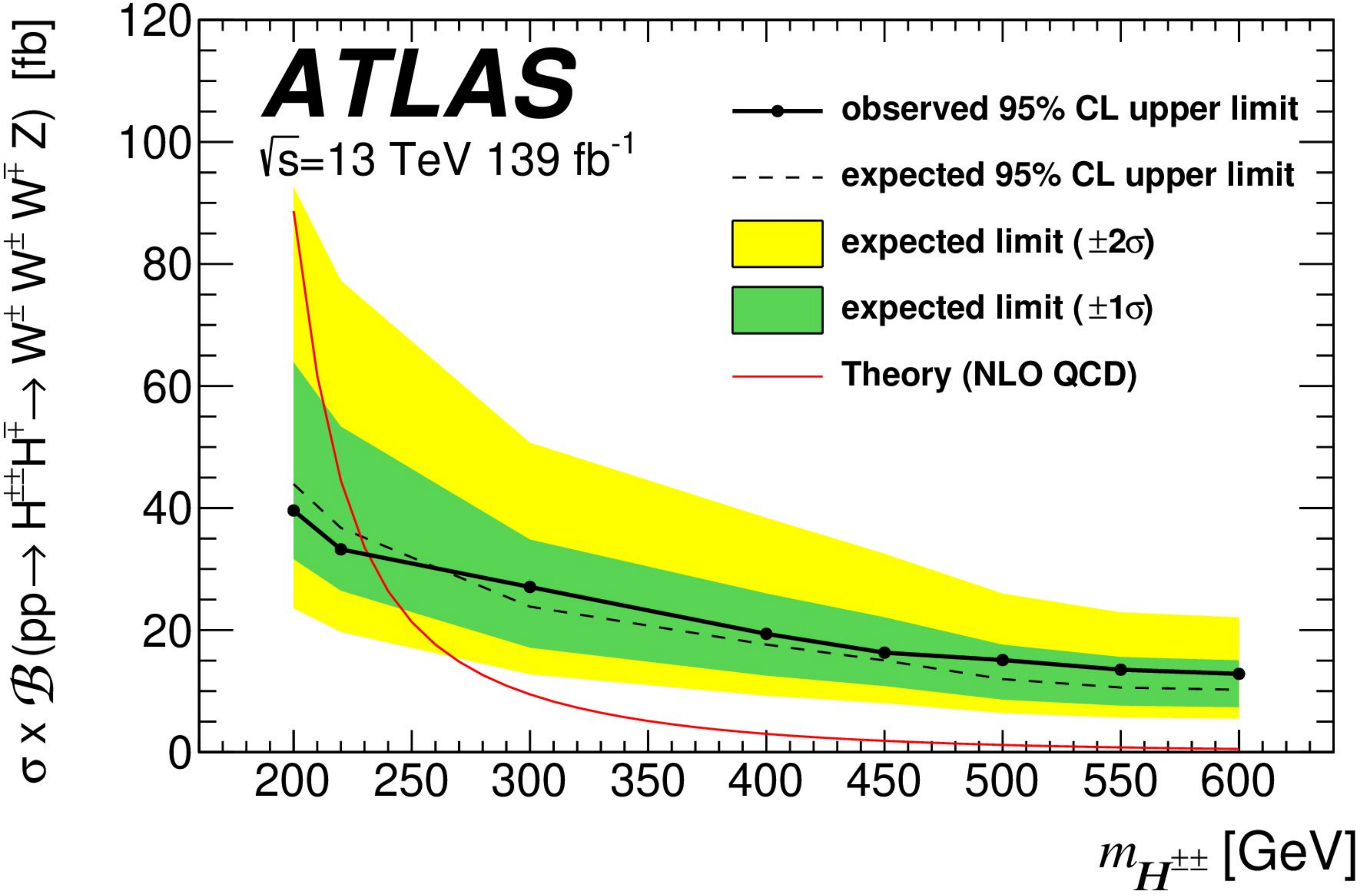
arXiv:2104.04762

Search for doubly and singly charged Higgs bosons:



[JHEP 06 (2021) 146]

Search for doubly and singly charged Higgs bosons:



JHEP 06 (2021) 146