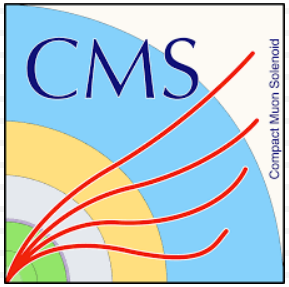
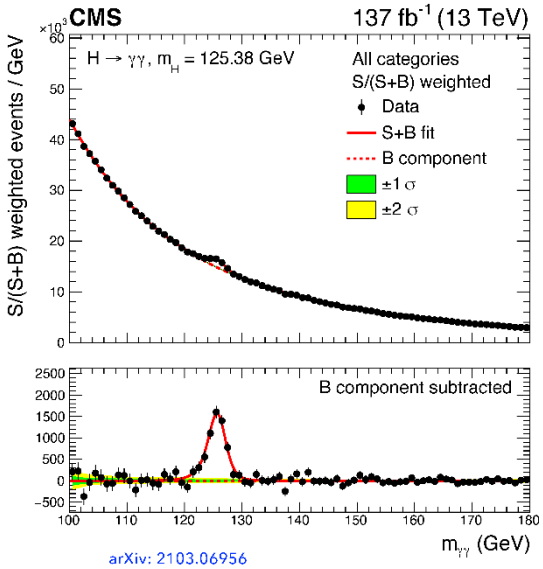
Searches for light scalar and charged scalar

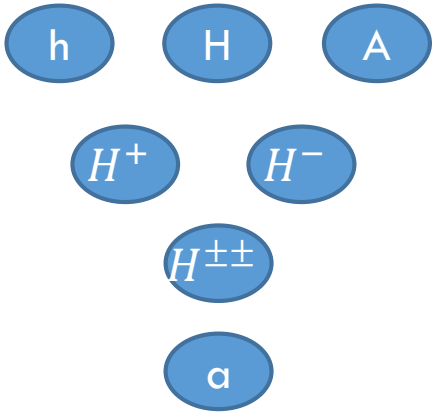


Jin Wang
Institute of High Energy Physics, CAS

Introduction

- Standard Model (SM) of particle physics is very successful in describing and predicting experimental results
  - discovery of Higgs in 2012: an important piece to complete SM
- Strong evidence that physics beyond SM (BSM) exist
  - neutrino masses, matter–antimatter asymmetry, dark matter, gravity and hierarchy problem etc.
- Many BSM theories predict additional Higgs like bosons
  - Two Higgs doublet models(2HDM) predict extended Higgs sector with neutral CP even (h/H), neutral CP odd (A) and charged Higgs bosons ($H^{\pm}$)
  - Other models (eg. 3HDM) extend to a Higgs triplet that gives doubly charged scalar Higgs
  - 2HDM plus singlet scalar (2HDM +S) or dark matter models predict spin-0, low-mass particles from Higgs exotic decays



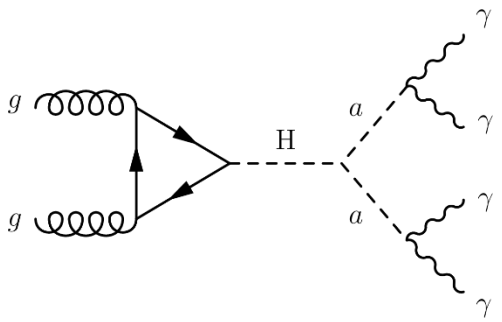


BSM Higgs searches in LHC

- Focus on recent BSM Higgs results from LHC on the following two directions
- Searches for light sector
  - direct searches for low-mass Higgs-like resonance
    - ATLAS: ATLAS-CONF-2018-025, CMS: Phys. Lett. B 793 (2019) 320
  - exotic Higgs decays to low-mass new particles
    - $H \to aa \to 4\gamma$: CMS-PAS-HIG-21-003
    - $H \to aa \to bb\mu\mu$: ATLAS-CONF-2021-009
    - $H \to XX/ZX \to 4l$: ATLAS-CONF-2021-034
- Searches for charged Higgs
  - $H^{\pm} \to tb$: JHEP 06 (2021) 145
  - $H^{\pm} \to cb$: ATLAS-CONF-2021-037
  - $H^{\pm} \to cs$: Phys. Rev. D 102 (2020) 072001
  - $H^{\pm} \to W^{\pm}Z$ and $H^{\pm\pm} \to W^{\pm\pm}$
    - ATLAS: JHEP 06 (2021) 146, see also talk by Hanlin XU
    - CMS: Eur. Phys. J. C 81 (2021) 723

$H \rightarrow aa$ searches

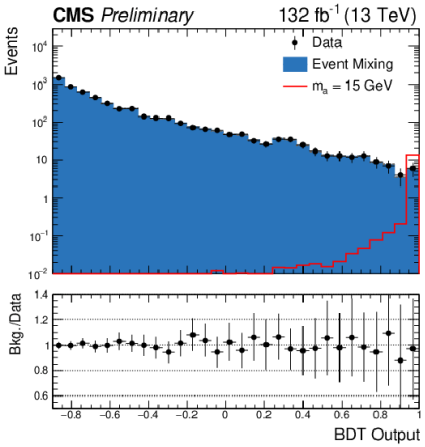
- $H \rightarrow aa$ possible in Next-to-MSSM with a as scalar or pseudo scalar
  - extended Minimal SUSY SM (MSSM) by adding singlet field
- A large number of searches at the LHC
  - with many final states
    - $a \rightarrow bb$, $a \rightarrow \tau\tau$, $a \rightarrow \mu\mu$, $a \rightarrow \gamma\gamma$

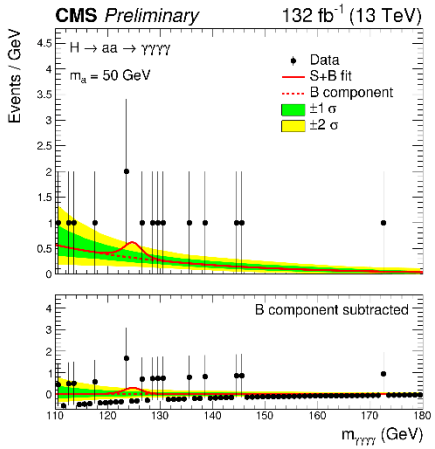


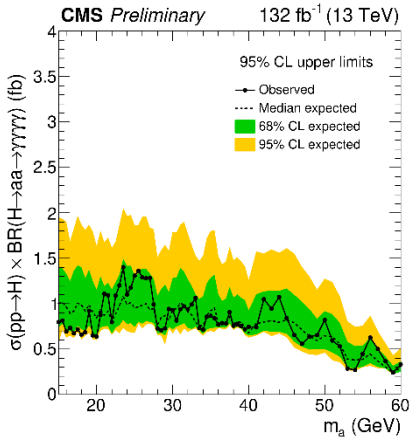
  - scanning m_a ranges up to $m_a \leq m_h/2$

$H \rightarrow aa \rightarrow 4\gamma$

- Final states: 4 isolated photons with mass range $15GeV < m_a < 60GeV$
  - low statistics but also very low background contamination
- Boosted Decision Trees (BDT) is explored to separate signal from backgrounds
  - parameterized as a function of m_a
- Signal extracted by fitting $m_{4\gamma}$ spectrum to data
  - background modelled by sidebands with smooth falling shapes
- No significant deviation from the background-only hypothesis is observed

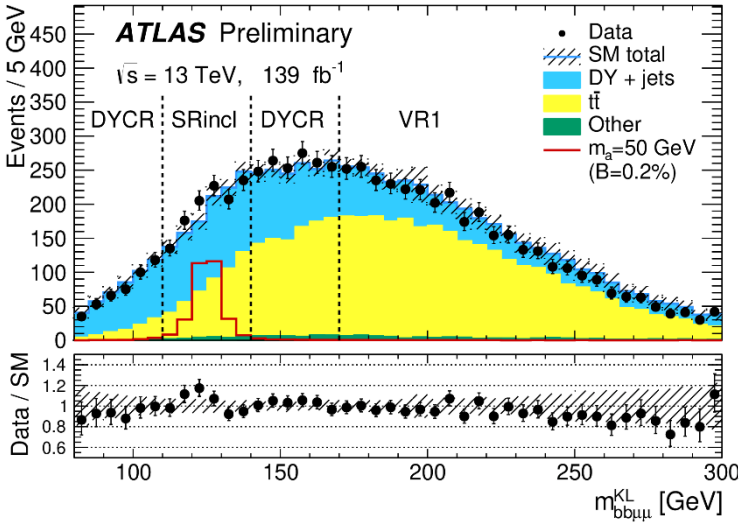


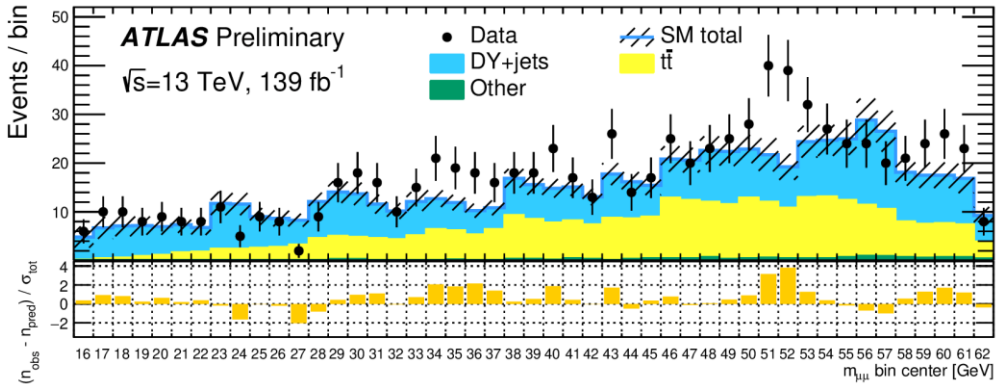




$H \rightarrow aa \rightarrow bb\mu\mu$

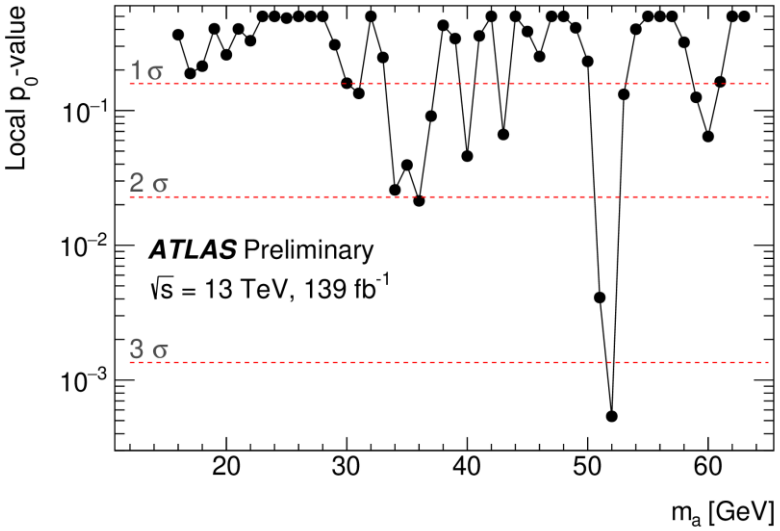
- Final states: two muons with two b-tagged jets
- Main background: ttbar and DY events
  - estimated from control regions
  - DY background reweighted from 0-b-tag region to 2-b-tag signal region
- BDT is trained to separate signal from backgrounds
  - with different $m_{\mu\mu}$ 8GeV windows

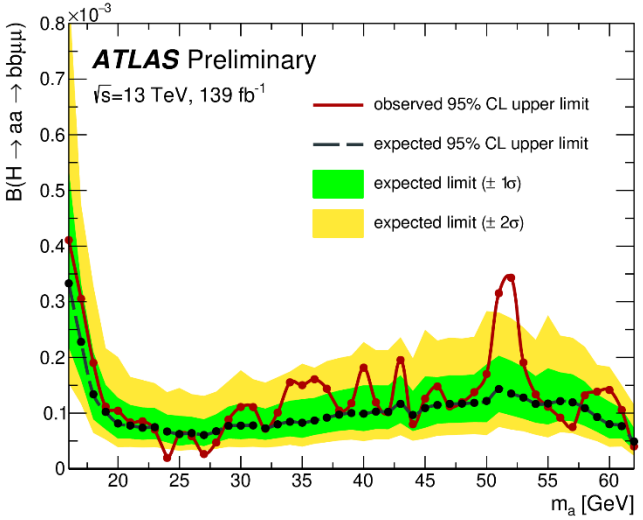




$H \rightarrow aa \rightarrow bb\mu\mu$

- Small excess of events above the Standard Model backgrounds
  - observed at an invariant dimuon mass of 52 GeV
  - local (global) significance of 3.3σ (1.7σ)
- 95% C.L. limits extracted for different signal masses



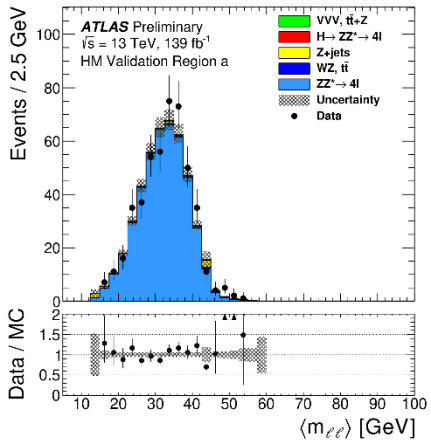


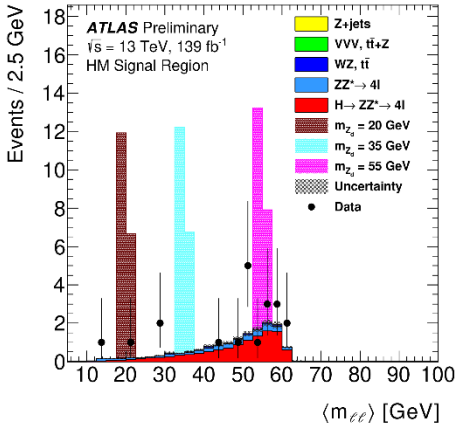
$H \rightarrow XX/ZX \rightarrow 4l$

- Dark matter and 2HDM models predicts mediator X
  - searches for $H \rightarrow XX/ZX$
- 4 lepton final state is explored
  - different phase spaces with different mass ranges

	Single Z (ZX) analysis $H \rightarrow ZX \rightarrow 4\ell$ $(\ell = e, \mu)$	High-mass (HM) analysis $H \rightarrow XX \rightarrow 4\ell$ $(\ell = e, \mu)$	Low-mass (LM) analysis $H \rightarrow XX \rightarrow 4\mu$
Mass range	$15\,\text{GeV} < m_X < 55\,\text{GeV}$	$15\,\text{GeV} < m_X < 60\,\text{GeV}$	$1\,\text{GeV} < m_X < 15\,\text{GeV}$

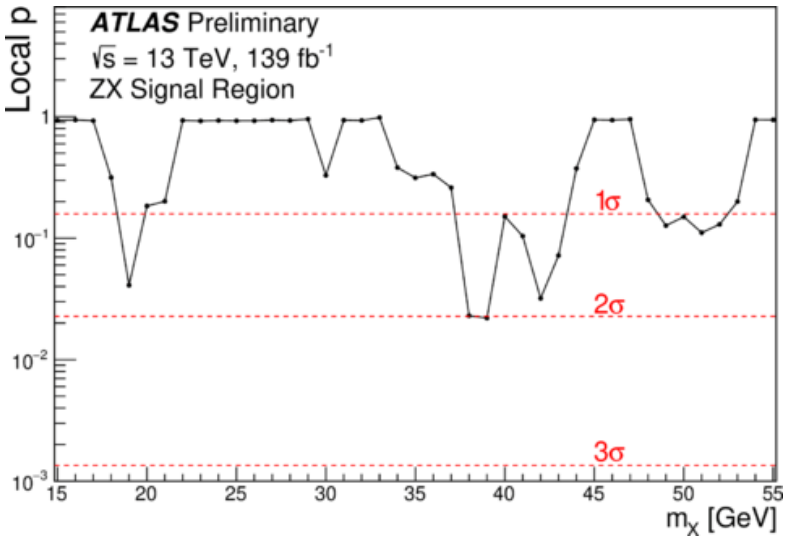
- Main backgrounds: $H \rightarrow \text{ZZ}$ and non-resonant ZZ events
  - estimated using MC and data-driven method separately
- Signal extracted from binned-fit to di-lepton masses

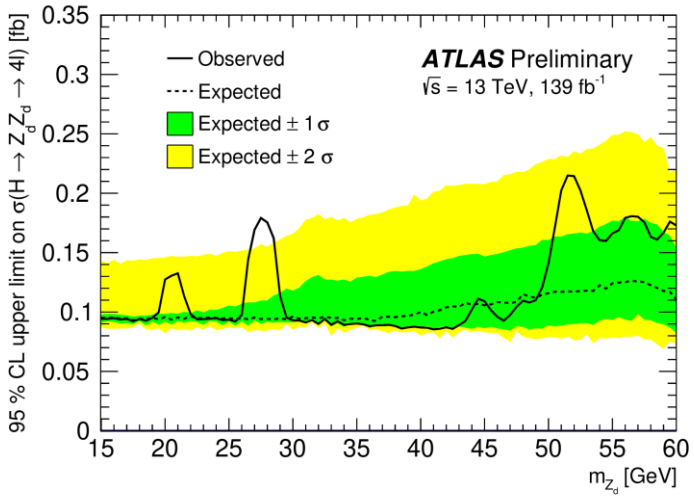




$H \rightarrow XX/ZX \rightarrow 4l$

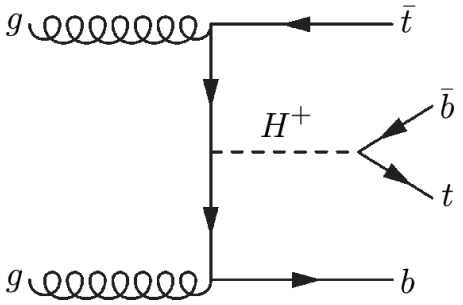
- Signal extracted from binned fit to di-lepton mass of data
- No significant excess over backgrounds
- Limits extracted for all 3 searches



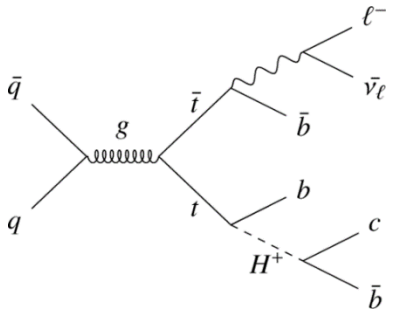


Charged Higgs searches

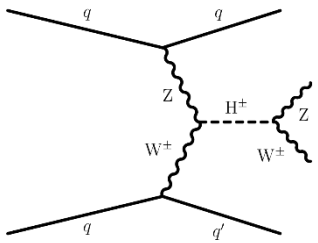
- Extended Higgs sectors with additional SU(2) doublets or triplets predict singly and doubly charged Higgs

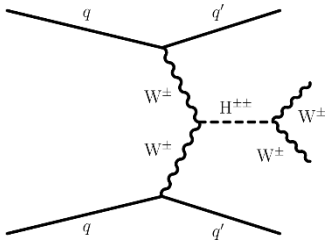


- Many searches with different decays of singly charged Higgs are explored at the LHC



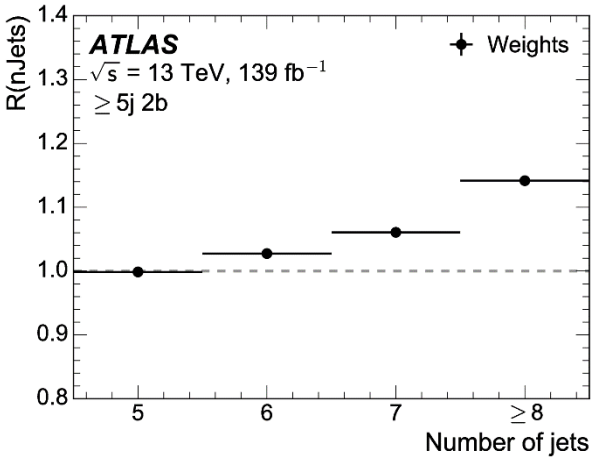
- Singly/Doubly charged Higgs bosons decaying into vector bosons

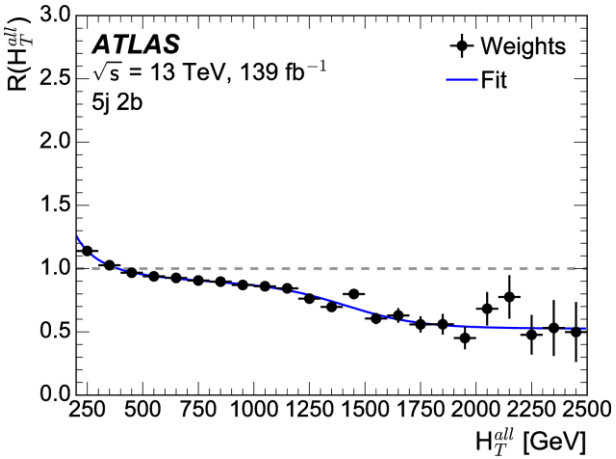


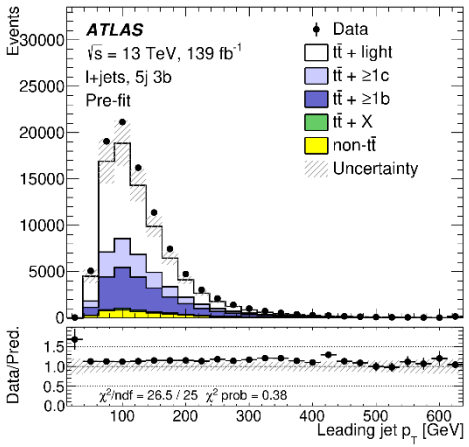


$H^{\pm} \rightarrow tb$

- $H^{\pm} \rightarrow tb$ is the primary decay mode for $m_{H^+} > m_t$
- Final states: lepton+jets with 4 signal regions
  - 5j 3b, 5j ≥4b, ≥6j 3b, ≥6j ≥4b
- Background dominated by top processes
  - estimated from MC
  - with data-based correction to tt+jets background

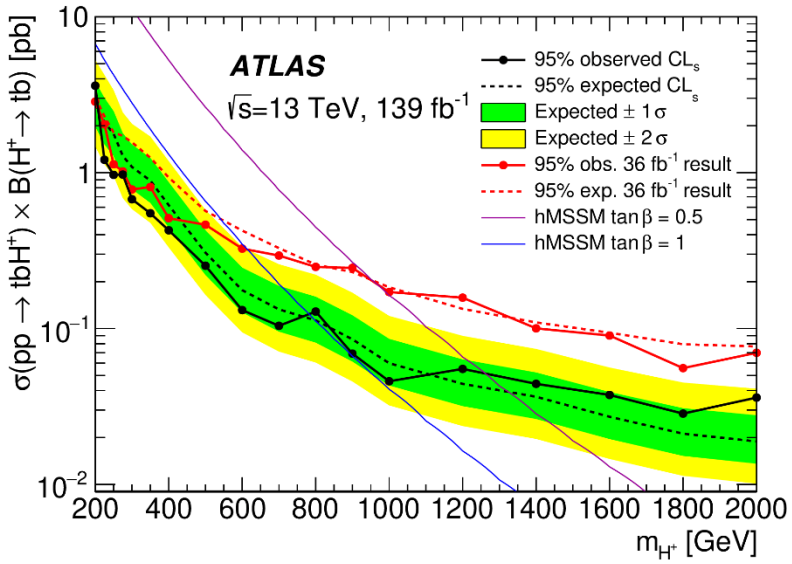


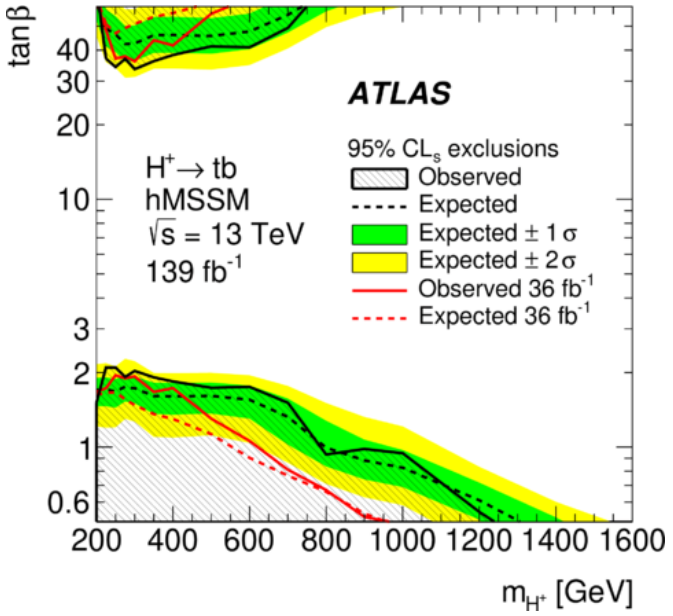




$H^{\pm} \to tb$

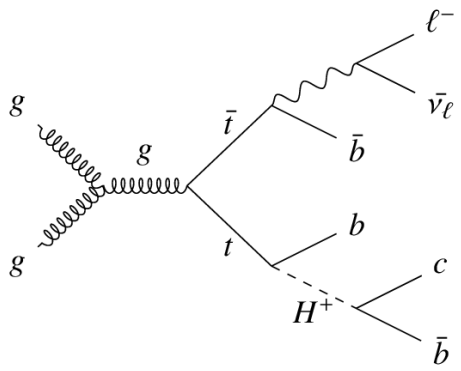
- Neural Network (NN) classifier is trained to separate signal and backgrounds
  - parameterized as a function of signal masses
- Signal extracted by simultaneous fits of NN outputs in 4 signal regions
- No significant excess observed from data
  - most sensitive channel for low $\tan\beta$

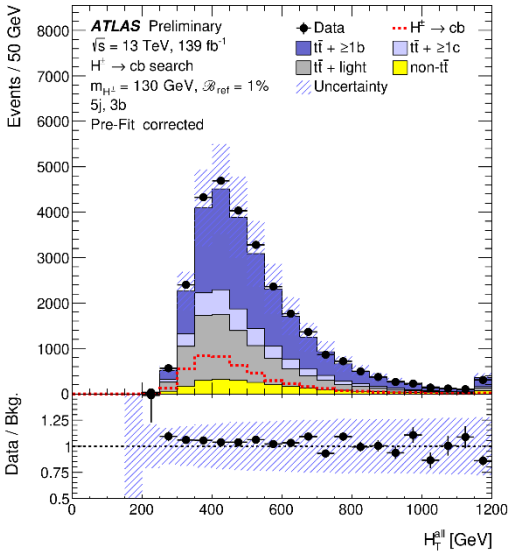


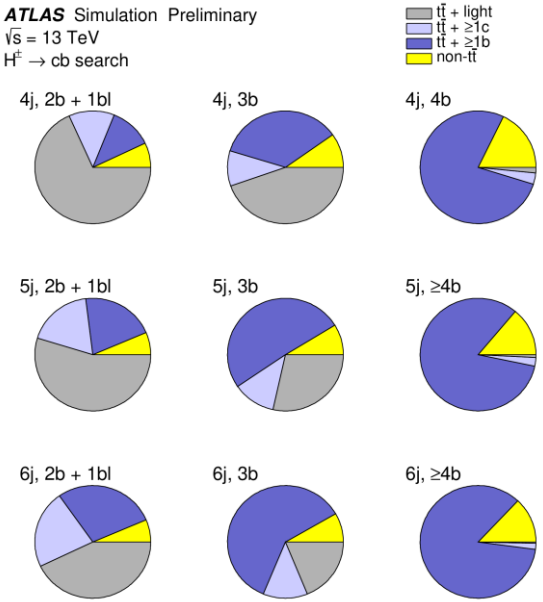


$H^{\pm} \rightarrow cb$

- In 3HDM lightest $H^{\pm}$ can be lighter than top quark
  - predominantly decays into cb
- Final states: 1 lepton, 3 b-jet, 1 c-jet
- Main backgrounds: tt+jets
  - modelled using simulation
  - corrected with a data-driven methods
- Events categorized based on jet and b-jet numbers



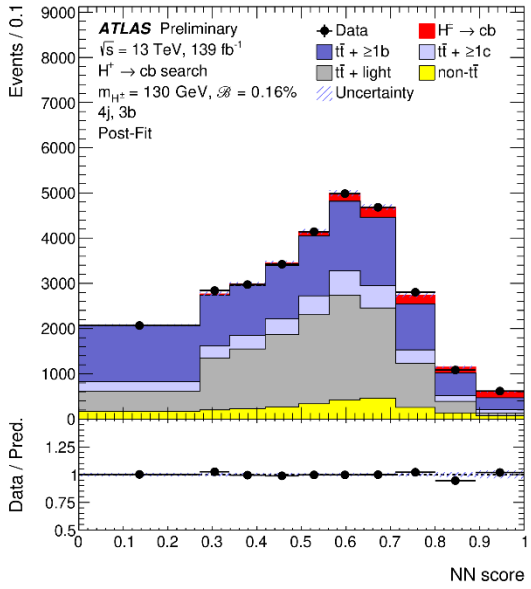


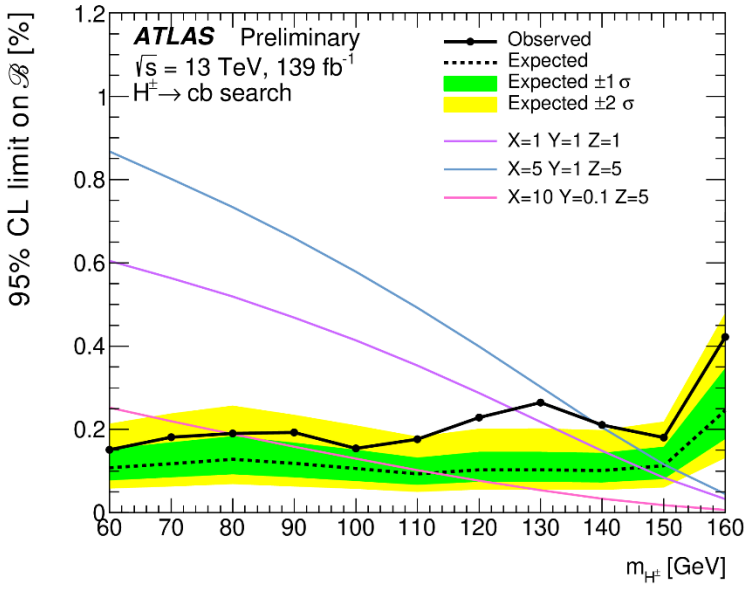


$H^{\pm} \rightarrow cb$

- Neural Network (NN) classifier is explored to separate signal from backgrounds
  - parameterized as a function of signal masses
- Signal extracted from binned fit of NN outputs in different signal regions
- Small excess observed at 130GeV
  - local (global) significance of 3σ (2σ)

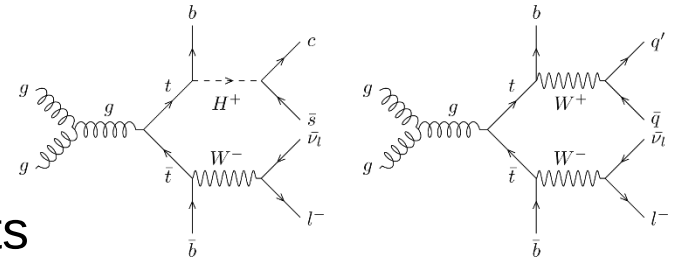
3HDM benchmarks from [Int. J. Mod. Phys. A 32 (2017) 1750145; Phys. Rev. D 98 (2018) 115024]

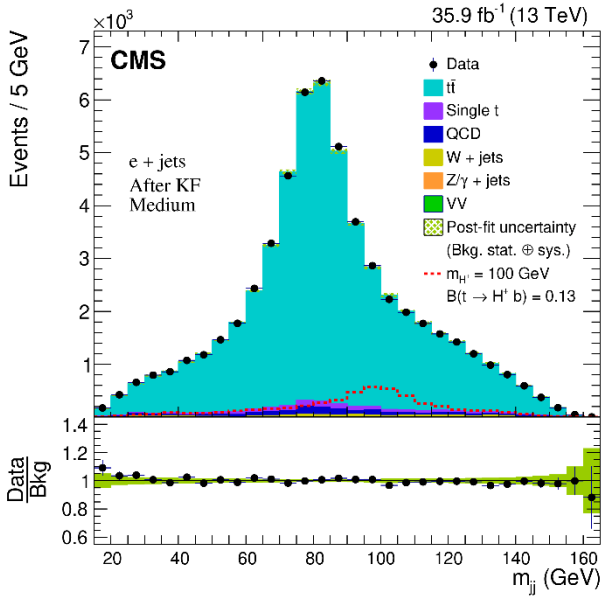


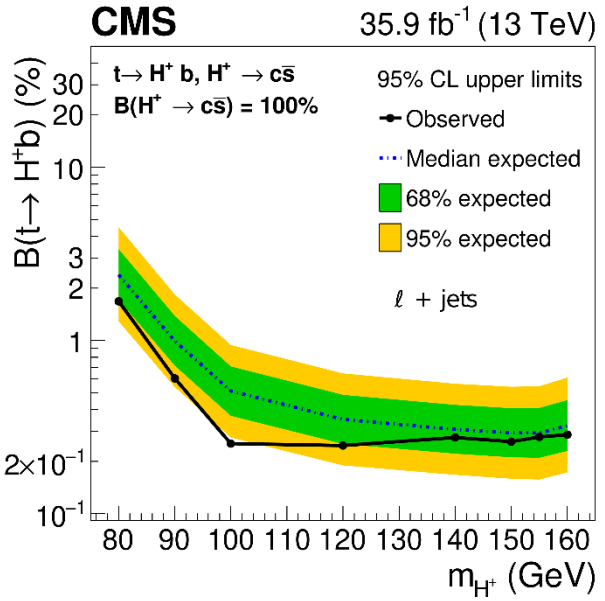


$H^{\pm} \to cs$

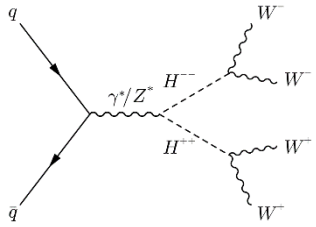
- Light charged Higgs from top decays with final states of 1 lepton and above 4 jets
- Main background from tt events
  - full reconstruction using kinematic fits
- Signal categorized based on c-tag ouputs
- No excess observed from data
  - upper limits extracted assuming $\mathrm{BR}(H^{\pm} \to cs) = 1$

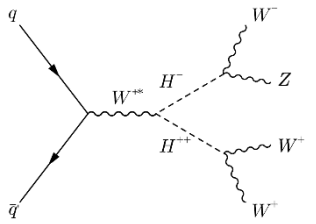


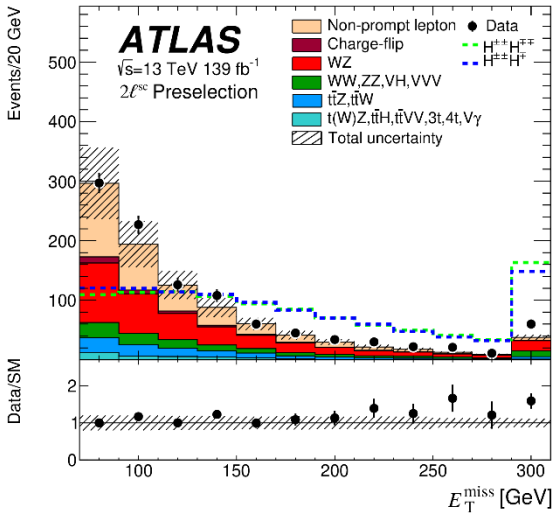


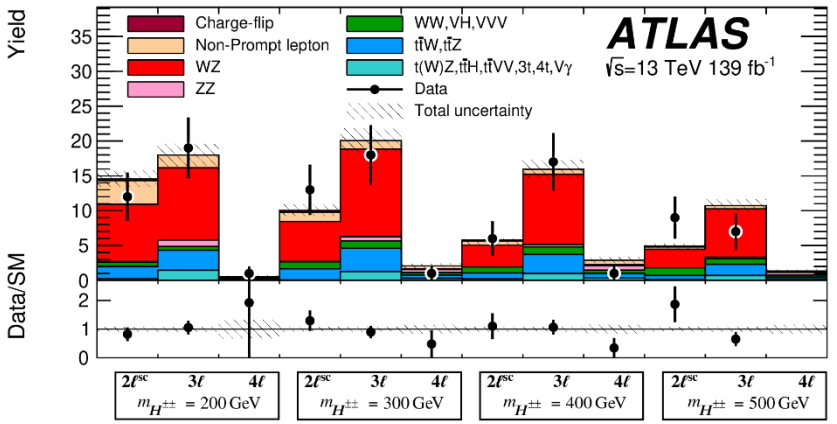


- Target pair and associate production modes where $H^{\pm\pm}$ predominantly decay to WW
- Final states: multi-leptons, MET and jets
- Main backgrounds:
  - SM WZ, non-prompt leptons, electron charge-flip
  - data-driven corrections applied to improve the background modelling
- Signal selection optimized for each lepton regions and different signal masses

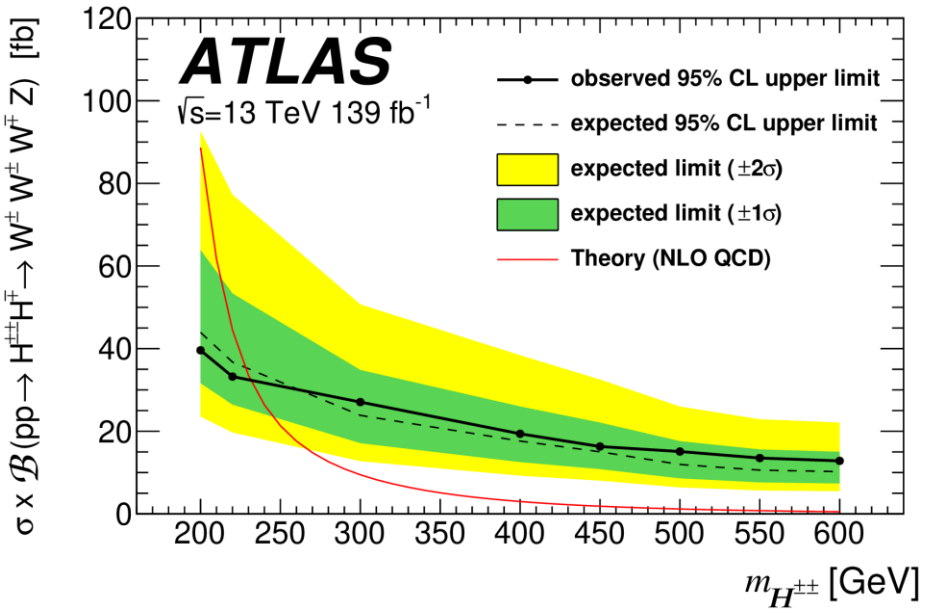


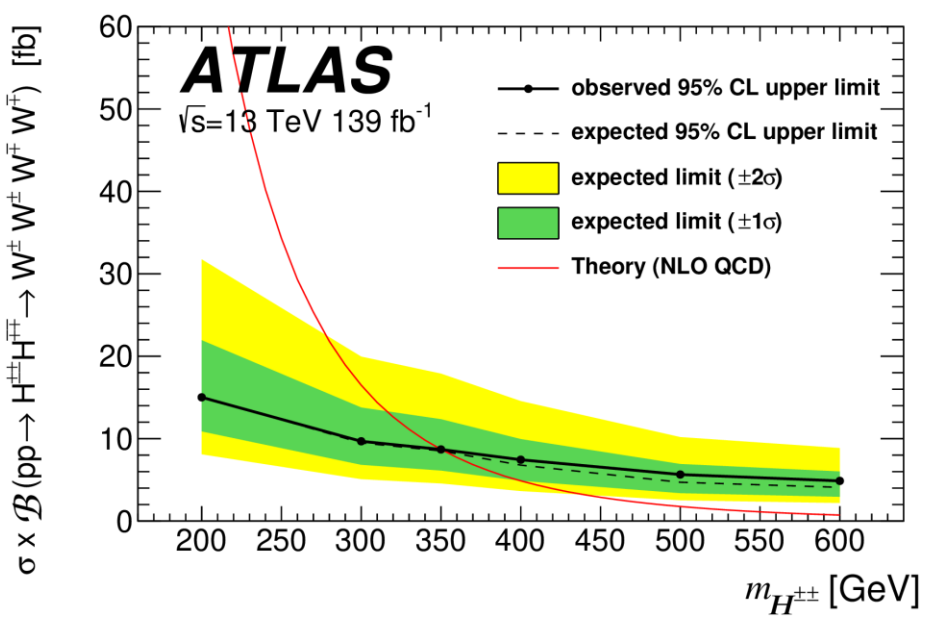




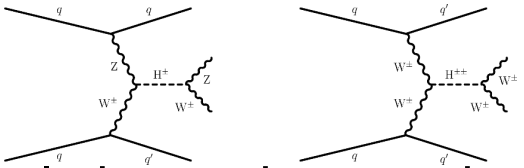


- Limits extracted from profiled likelihood fits for different sigal masses combined all signal categories
- No significant deviations from the Standard Model predictions are observed
- $H^{\pm\pm}$ excluded at 95% C.L. up to 350 GeV and 230 GeV for the pair and associated production modes

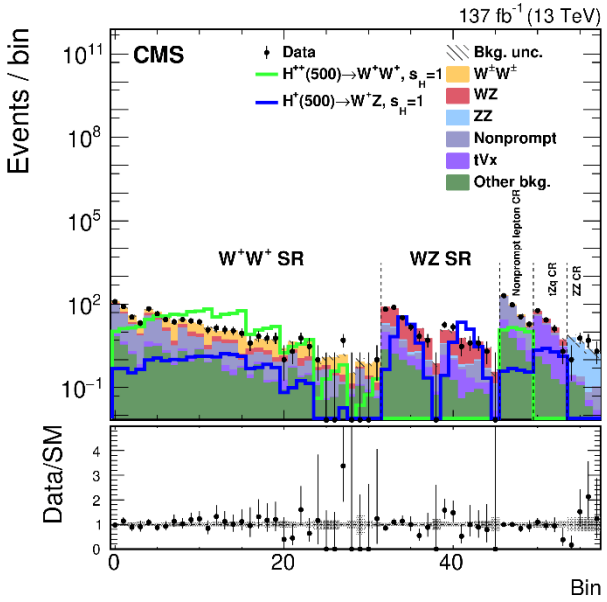


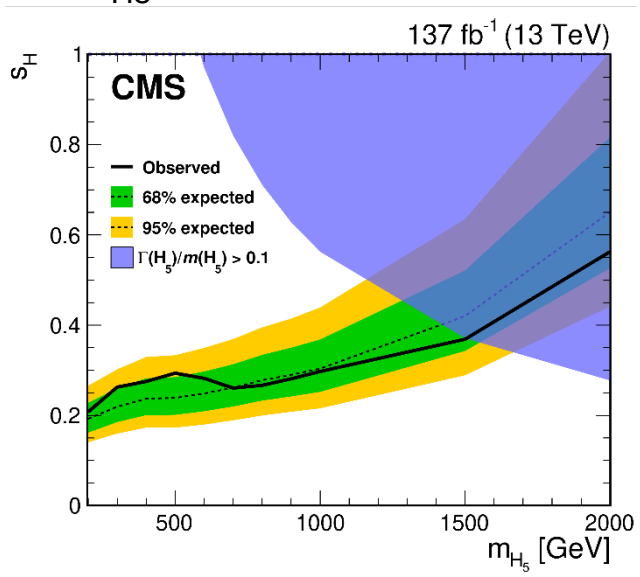


- Target VBF singal with mjj > 500 GeV and $|\Delta\eta_{jj}| > 2.5$ for leading two jets



- Background estimated based on simulation and constraints from three control regions (CRs)
  - noprompt lepton CR, tZq CR and ZZ CR
- No significant deviation from SM observed
  - s_H range of 0.20 to 0.35 excluded for m_{H5} of 200 to 1500 GeV





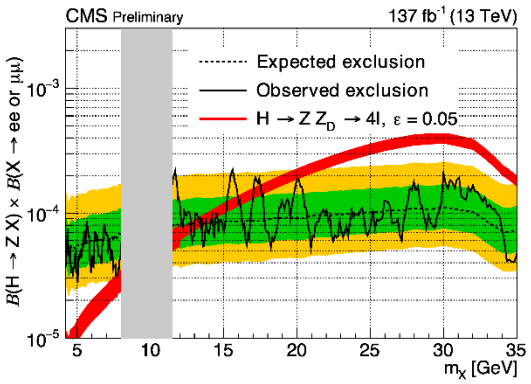
Summary

- A wide range of searches for BSM Higgs at the LHC
  - exotic Higgs decays to low-mass new particles
  - singly and doubly charged Higgs searches
- No significant excess found over SM predictions
- Large parameter space of BSM benchmarks are already excluded
  - significant improvements from optimization of object identification, MVA techniques and background modelling
- More results to come with full Run2 data, and Run3/HL-LHC

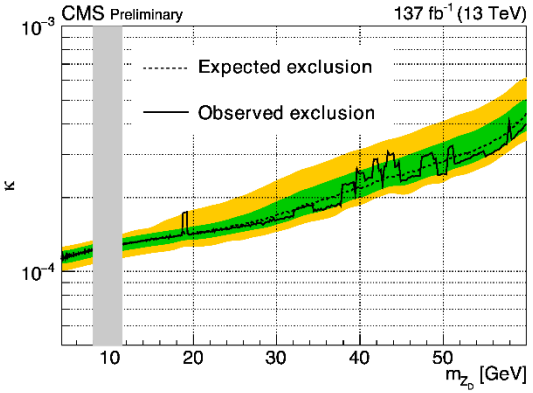
Back up

$H \to XX/ZX \to 4l$

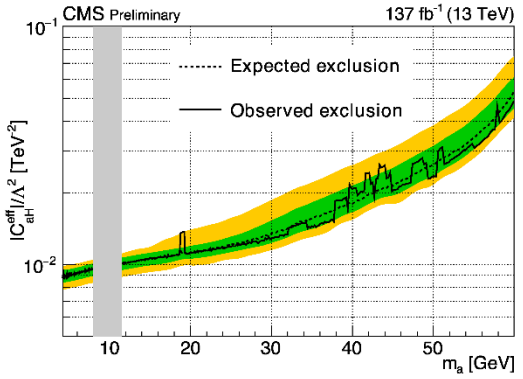
CMS-PAS-HIG-19-007



Model independent;
ZX selection



κ: Higgs mixing parameter
(Dark-photon model)



C_{aH}^{eff}: effective coupling of Higgs boson and ALP;
Λ: new physics scale

- No significant deviation from SM observed → strong limits set
- Several hundred mass hypotheses considered for both XX and ZX final states; excesses with largest local significance: 2.9 and 3.0σ at m_X of 18.8 and 15.6 GeV, respectively
- Limits on production cross-section times branching fraction interpreted in terms of dark-photon and ALP models