BSM and Rare Higgs from ATLAS and CMS

李冰 (Bing Li)

山东大学 (Shandong University)

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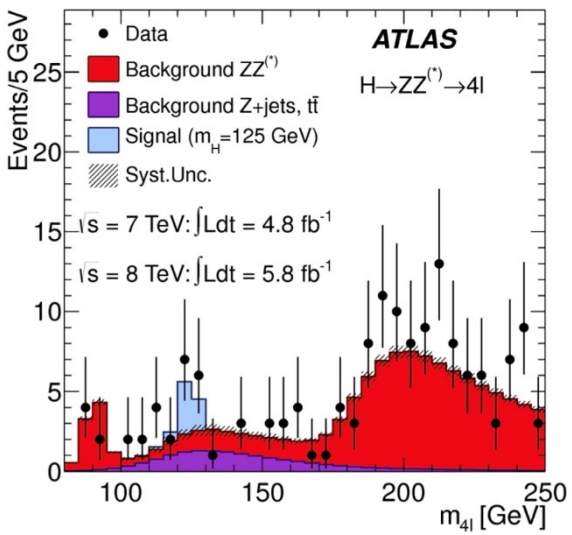
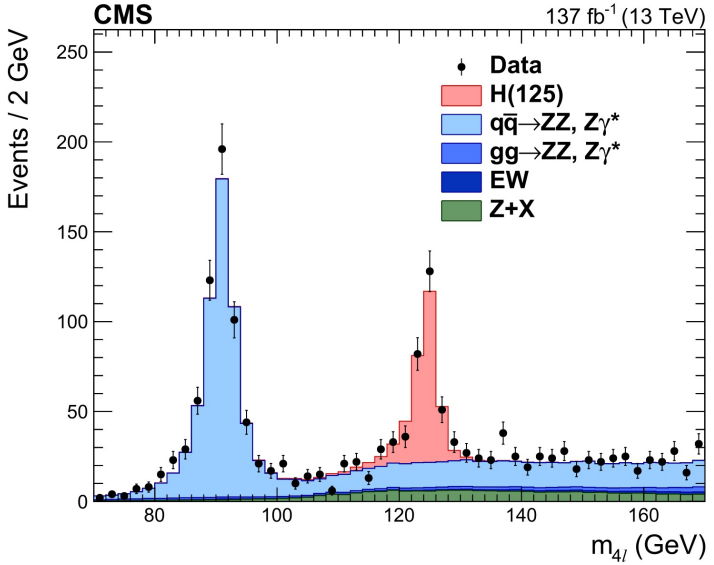
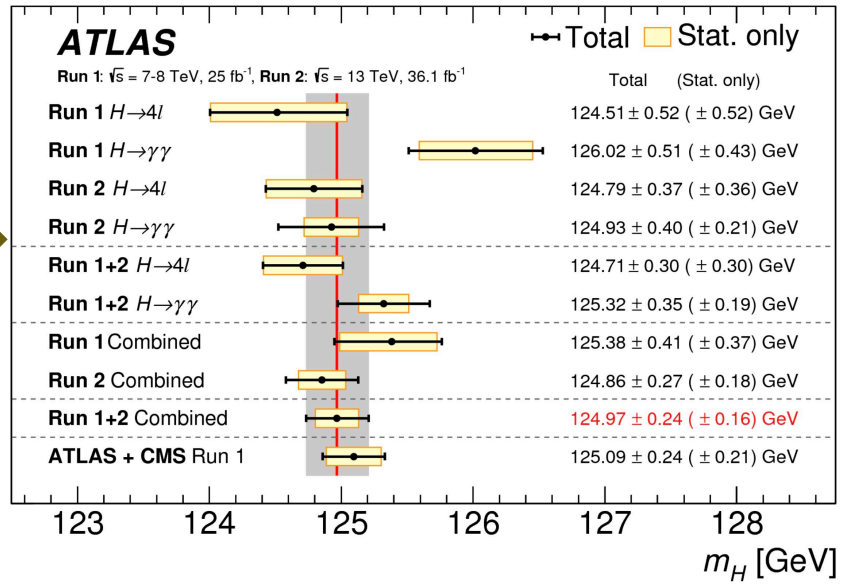
Nov. 25 to 28, 2021

Introduction

- The Higgs boson was discovered by the ATLAS and CMS experiments at the LHC in 2012.
- By now, it has been observed in all the main production modes and many decay channels.







After the Discovery Stage

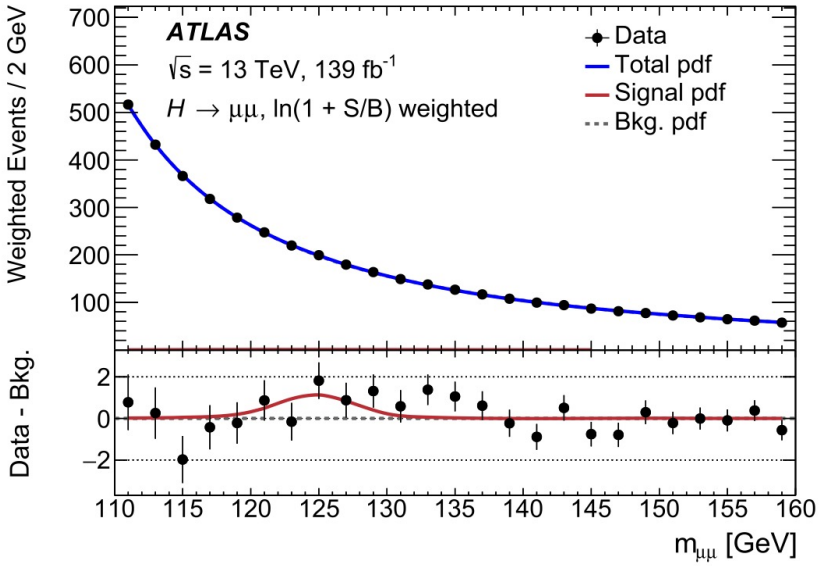
- Precision measurements
  - Measurement of Higgs properties (mass, width, spin, parity, couplings, cross sections etc) → see Chen Zhou's talk
- Searches for rare SM Higgs decays and BSM Higgs → contents of this talk
  - Rare SM Higgs decays: H → μμ, cc, Zγ …
  - Heavy Higgs. Charged Higgs. Higgs → light resonances. LFV …
- Dark matter and unconventional searches involving Higgs → see Lailin Xu's talk
- Searches for DiHiggs production → see Yanping Huang's talk

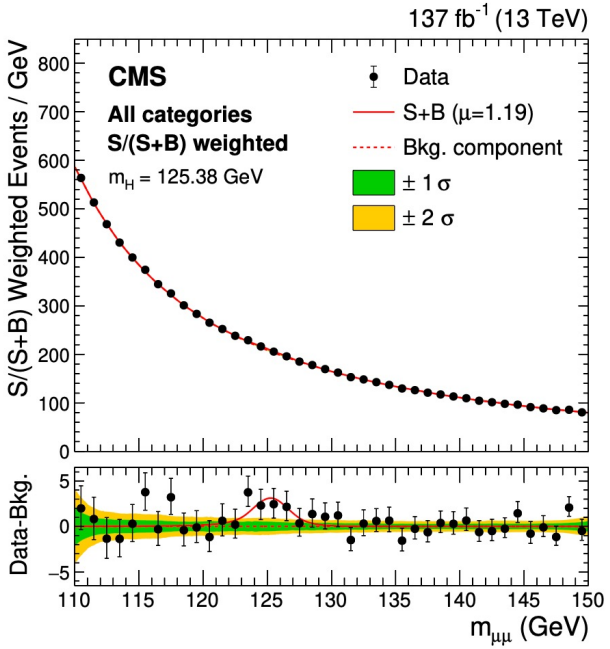
Full lists of ATLAS and CMS publications.

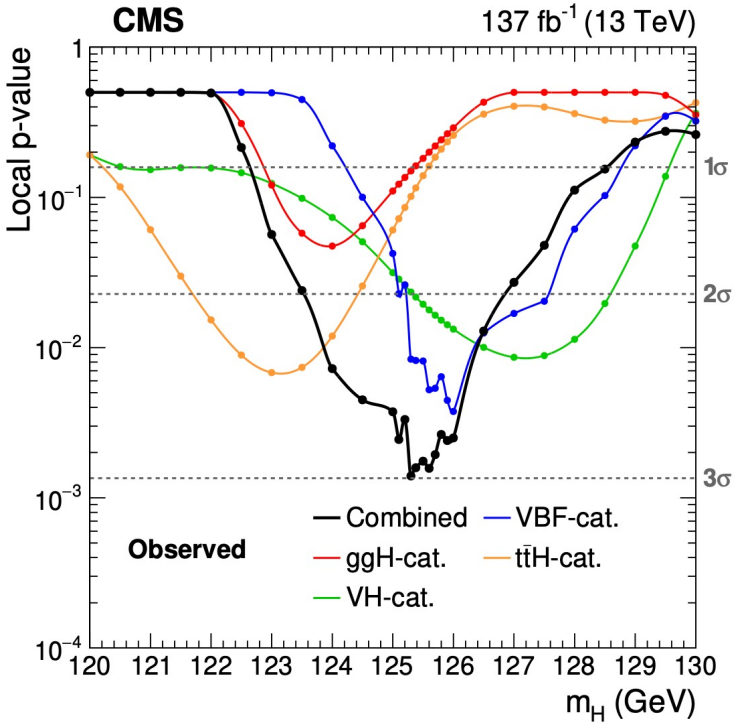
Higgs → μμ

Phys. Lett. B 812 (2021) 135980
JHEP01(2021)148

- Both analyses include all four production modes with full Run 2 data
- Two muon final state gives good resolution but
  - BR is very low ($2.2*10^{-4}$)
  - Large background from Z → μμ (over all S/B ~10^{-3})
- Event categorization is important. MVA used to further separate signal and backgrounds.







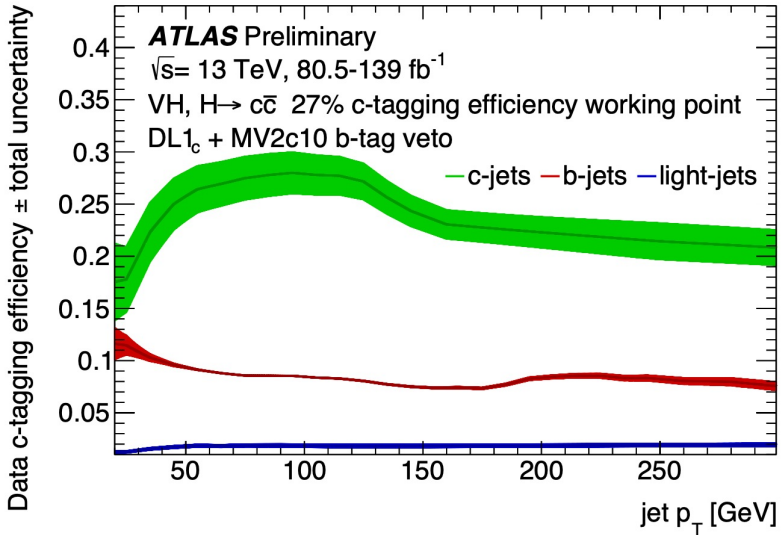
ATLAS:
Observed (expected): 2.0 (1.7) σ
Best-fit signal strength: 1.2 +- 0.6
CMS:
Observed (expected): 3.0 (2.5) σ, evidence
Best-fit signal strength: 1.19 +0.44 -0.42

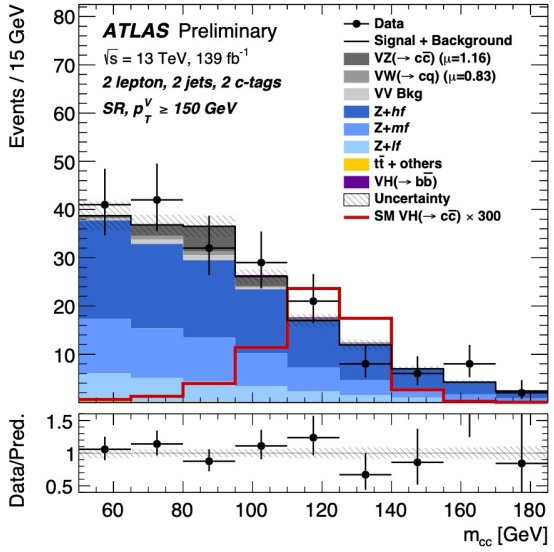
Higgs → cc

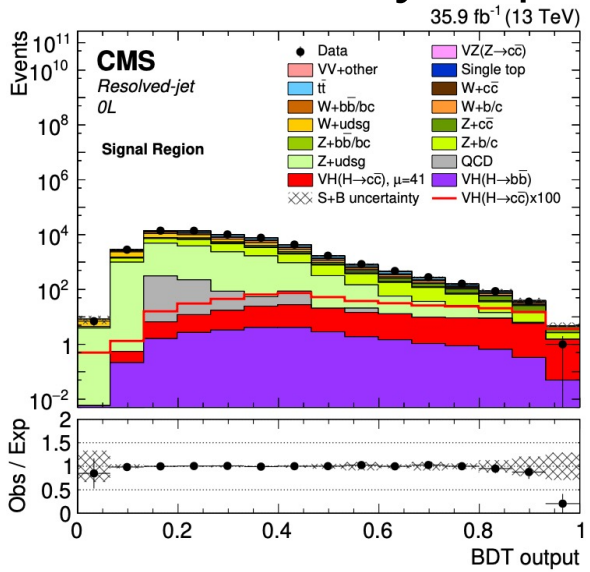
ATLAS-CONF-2021-021
JHEP 03 (2020) 131

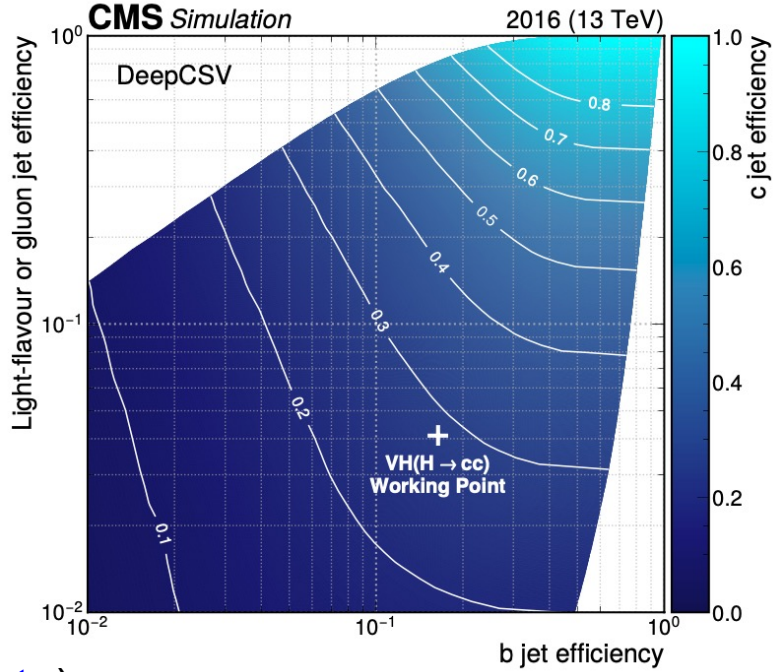
* Direct test of the Higgs-charm coupling.
  * BR ~2.9%. Not so low.
  * Background much more complicated.
  * c-tagging is very challenging.
* Analyses done in VH mode with V decays leptonically

Both analyses have developed dedicated c-tagging





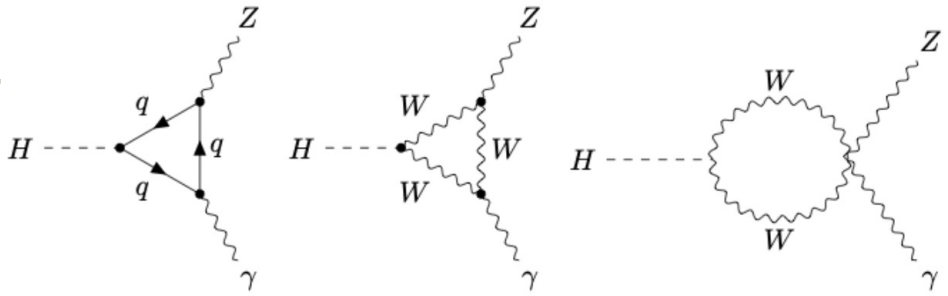




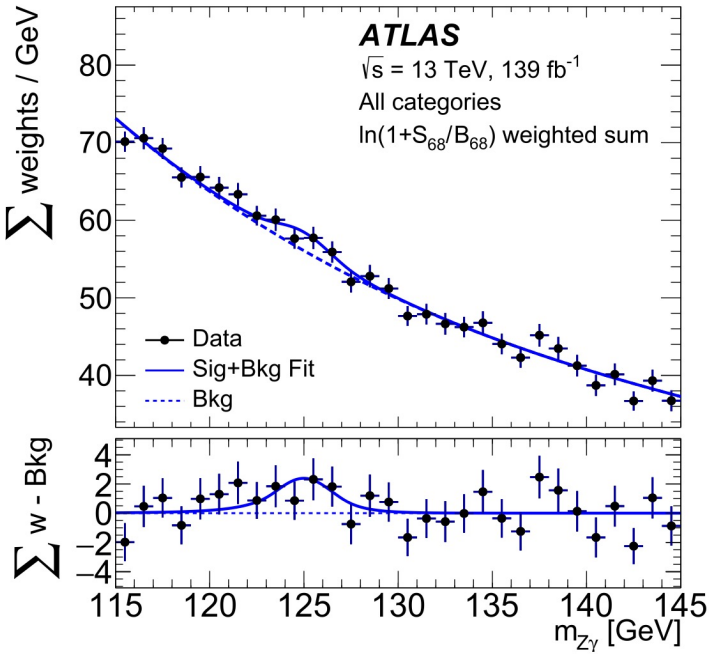
Observed (expected) upper limit: 26 (31) from ATLAS, 70 (37) from CMS (partial data)
CMS includes both resolved and merged jets

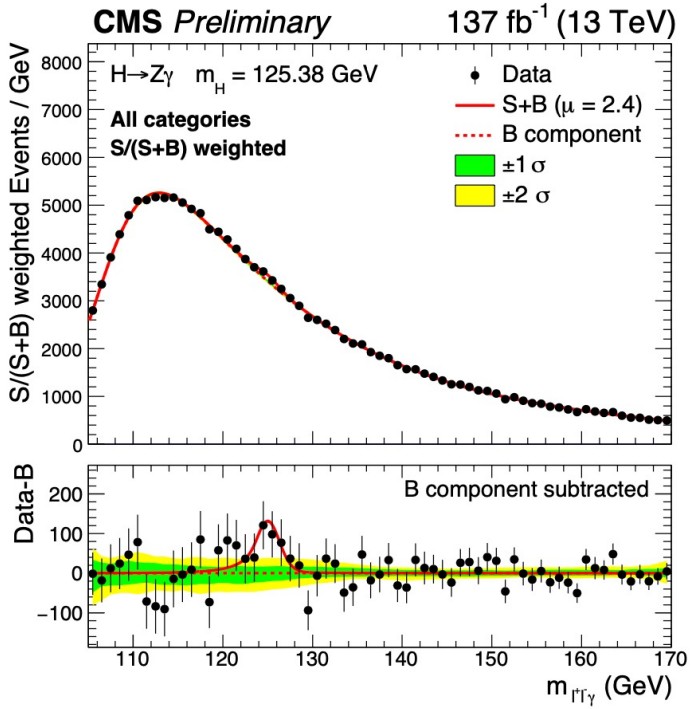
Higgs → Zγ

Phys. Lett. B 809 (2020) 135754
CMS-PAS-HIG-19-014



- Include all four production modes and full Run 2 data
- BR = $1.5*10^{-3}$. Analyses done in Z → ee/μμ ~7%.
- Events are further categorized to several signal regions based on lepton flavor, kinematics and BDT scores.



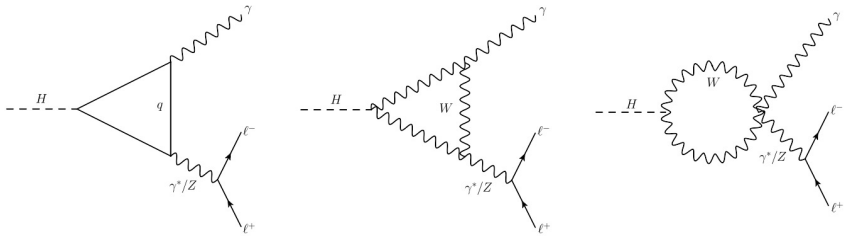


ATLAS:
Upper limit @95% CL: 3.6 *SM
Best-fit signal strength: 2.0 +1.0 -0.9
CMS:
Upper limit @95% CL: 4.1 *SM
Best-fit signal strength: 2.4 +- 0.9

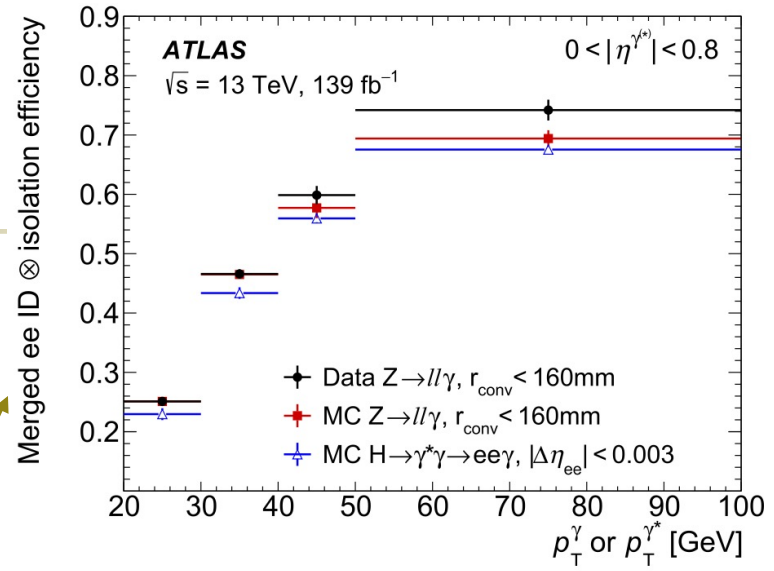
Higgs → llγ

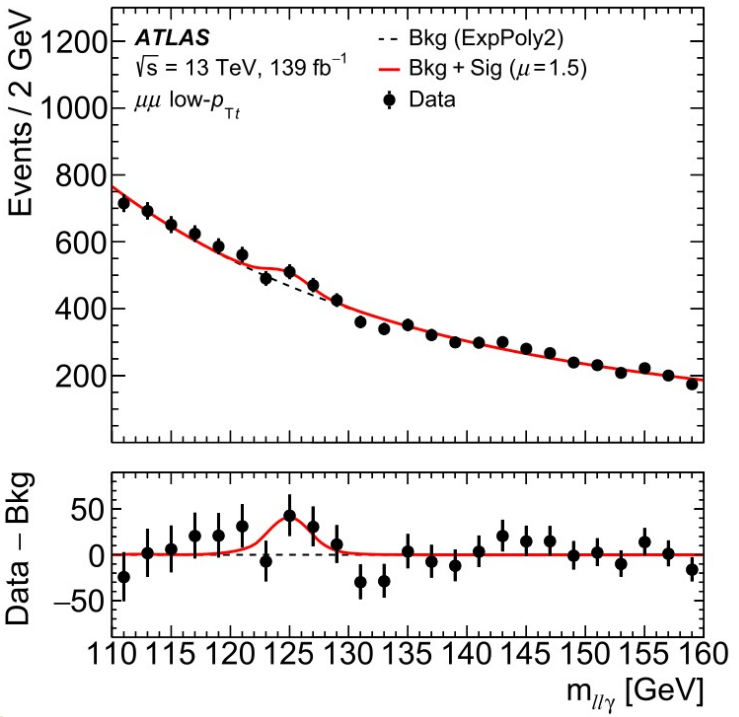
Phys. Lett. B 819 (2021) 136412

- ATLAS has a dedicate search at low m_{ll} region below 30 GeV, with J/ψ and Υ regions excluded with full Run 2 data
- Dominant by decay through γ*.



- ee in the eeγ channel could be offten reconstructed as a single cluster in EM calorimeter → dedicated ee ID has been developed
- Events classified into different categories based on lepton flavor and event topologies
- Observed (expected) significance: 3.2 (2.1) σ evidence
- Measured signal strength 1.5 +- 0.5, with cross section 8.7 +2.8 -2.7 fb





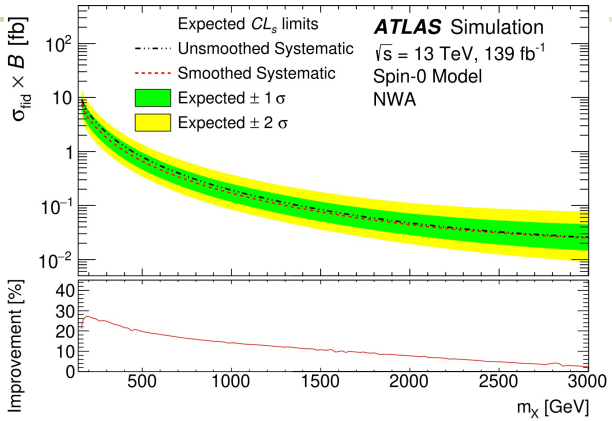
Searches for High Mass Higgs

- High mass spin-0 particles are predicted by several models with extensions to the Higgs sector.
- ATLAS and CMS have established searches for those high mass resonances in all diboson channels.
- Results are often also interpretated as other models as well, like a spin-2 particle.

Phys. Lett. B 822 (2021) 136651

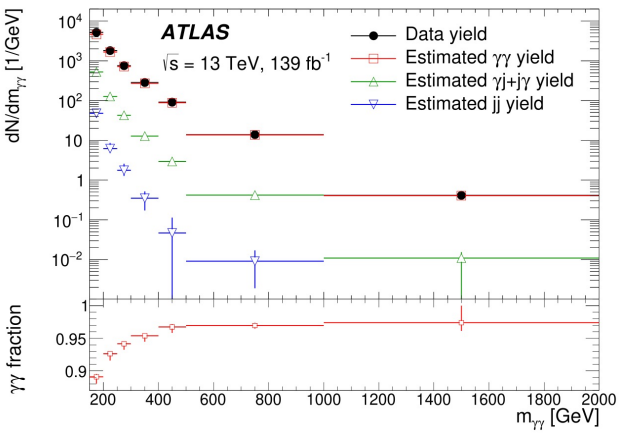
High Mass Resonance Searches in γγ Channel

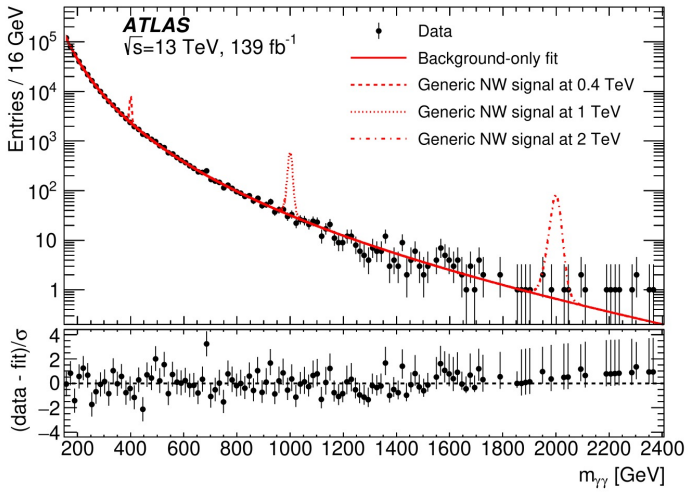
- An update from ATLAS using full Run 2 data
  - Common event selection used for the spin-0 and spin-2 resonances searches
  - Functional decomposition method used to estimate spurious-signal
- Major background from the SM γγ process.



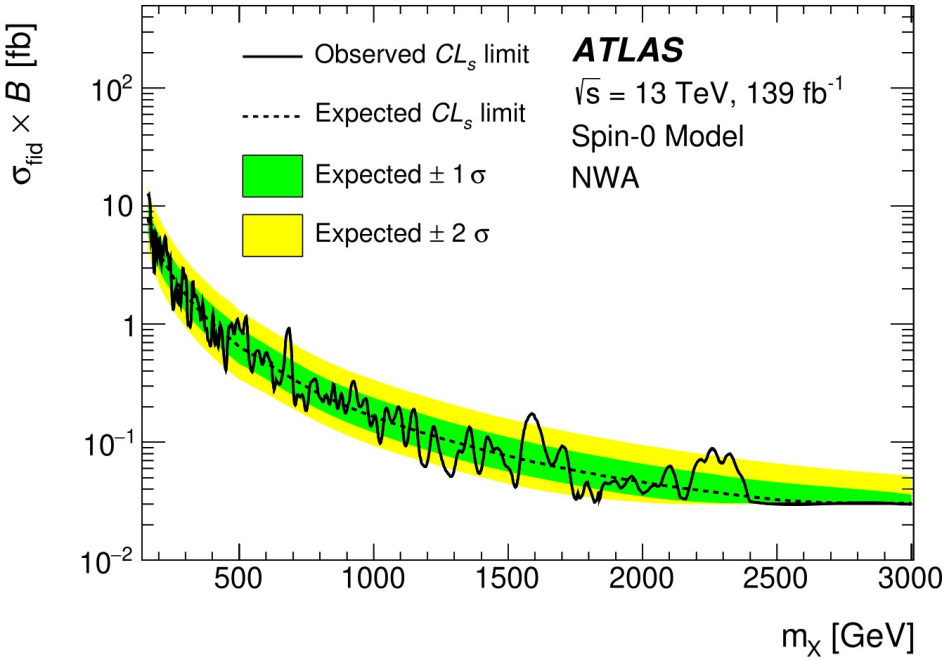
Improvement from FD method

Pseudo-experiments for illustration only





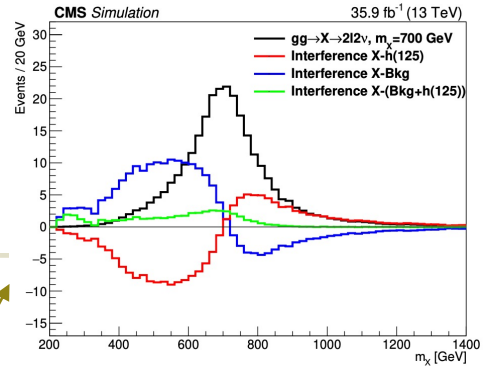
Background composition

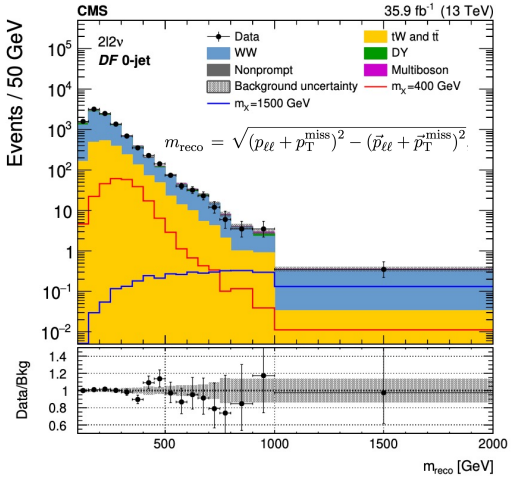


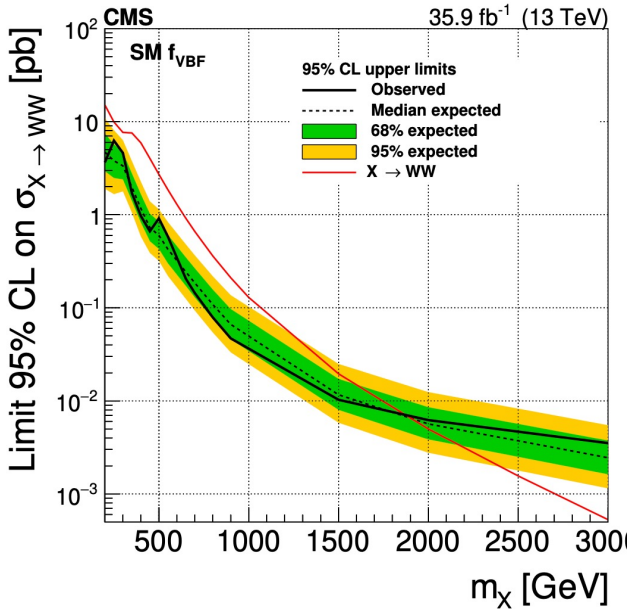
High Mass Resonance Searches in WW Channel

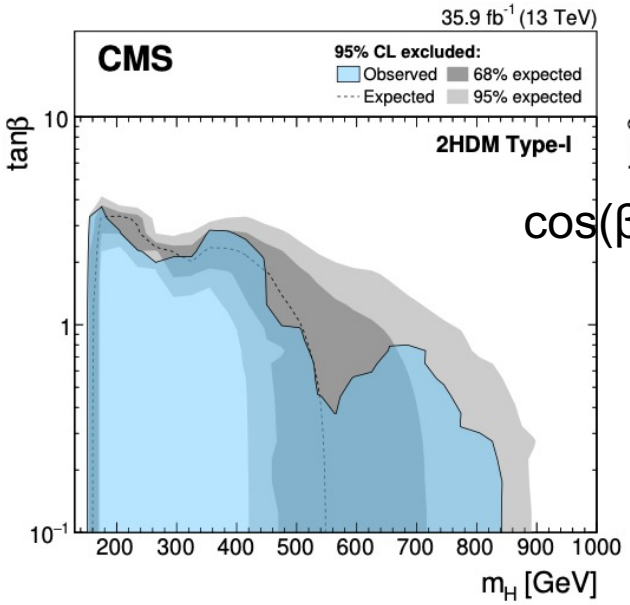
JHEP 03 (2020) 034

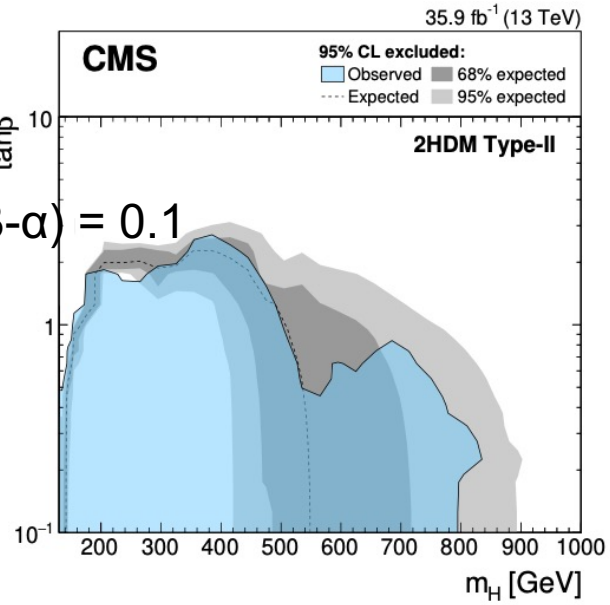
- CMS has a recent search in WW channel with 35.9fb^{-1} data
- Include both the lvlv and lvqq (both resolved and boosted) final states.
- Events are categorized in ggF and VBF categories
- Interferences between X and SM are considered for large width signals
  - X-h(125) and X-continuum interferences have opposite signs



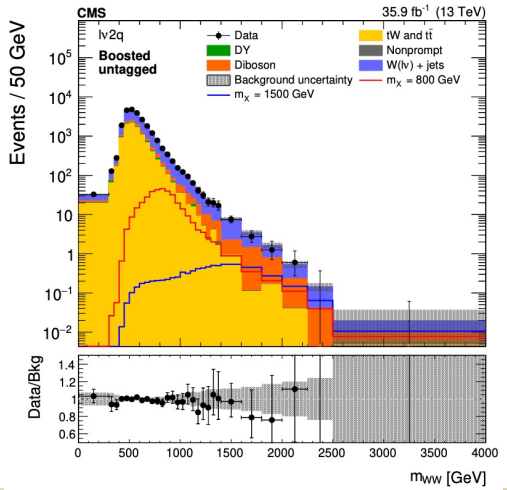








cos(β-α) = 0.1

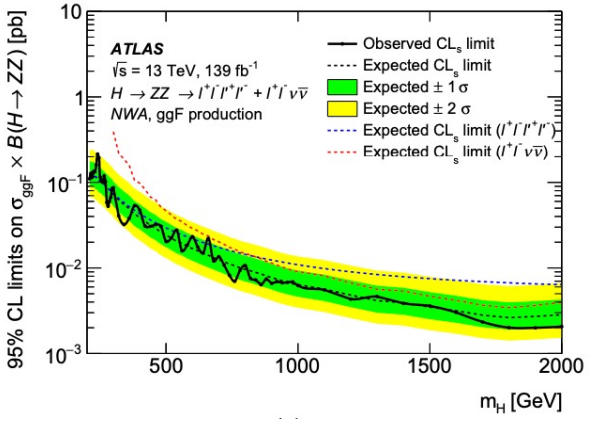


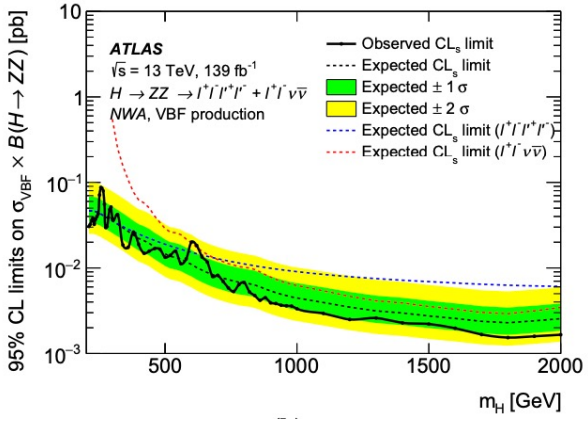
Eur. Phys. J. C 81 (2021) 332

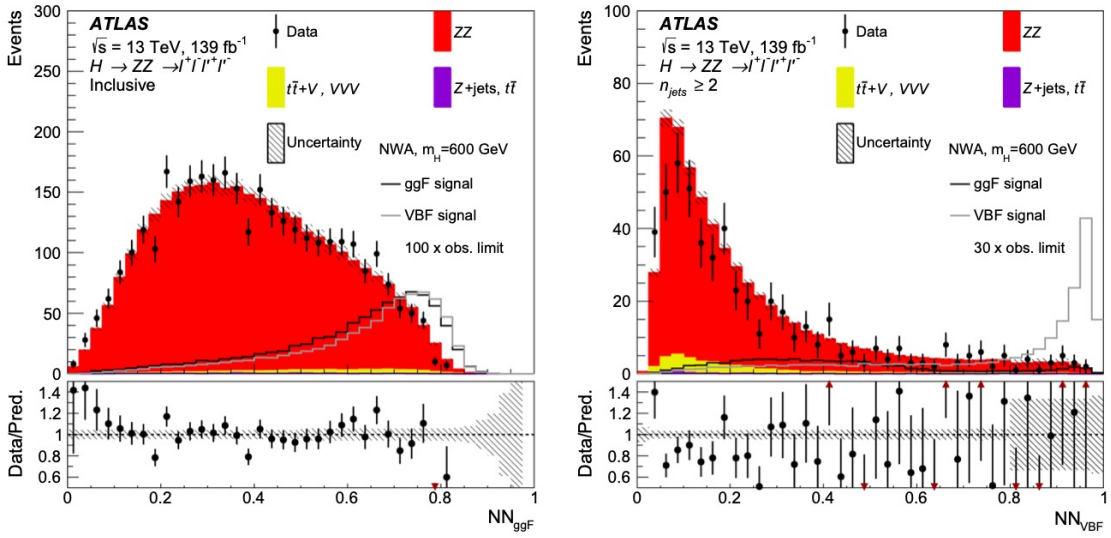
High Mass Resonance Searches in ZZ Channel

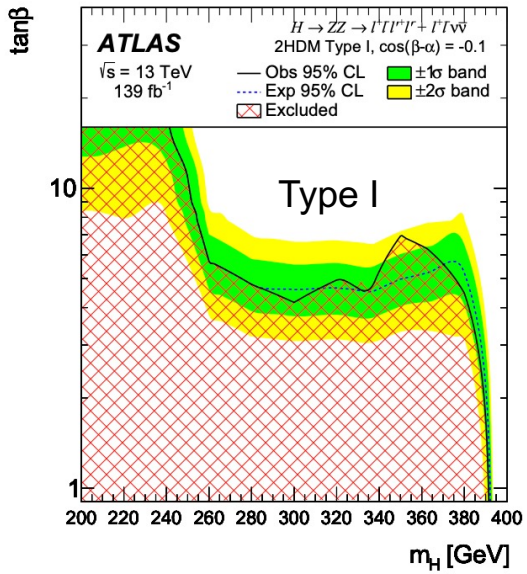
llvv more sensitive in high mass region

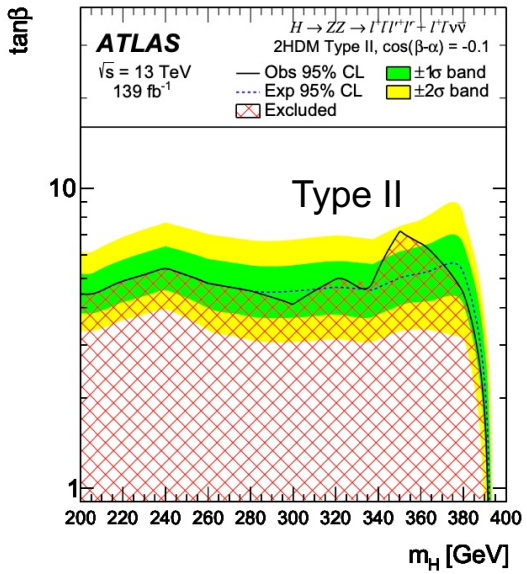
- ATLAS has published searches in ZZ channel in the 4l and llvv final state with full Run 2 data
- Two channels are sensitive to different mass regions
- Events are categorized in ggF and VBF channels
- Interferences are considered for large width signals
- DNN used in 4l channel for categorization







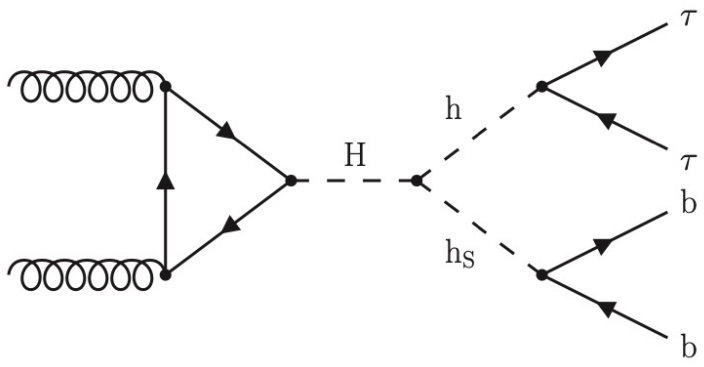


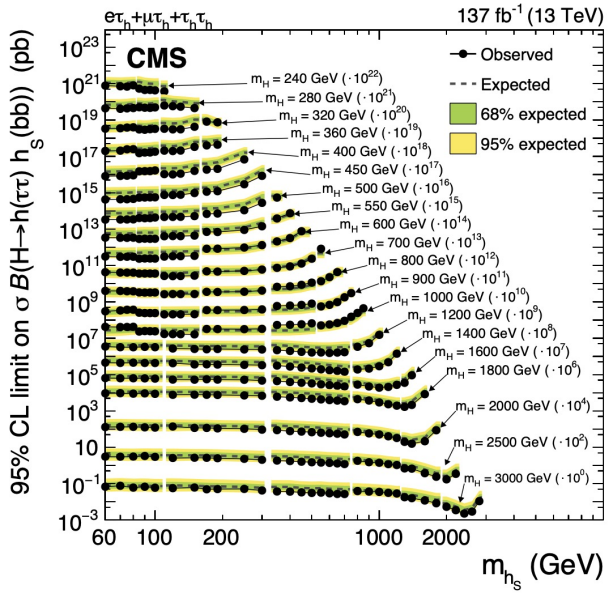


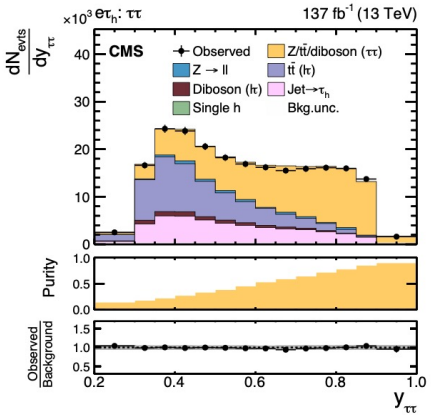
Search for Heavy Higgs to h(125) and h_s

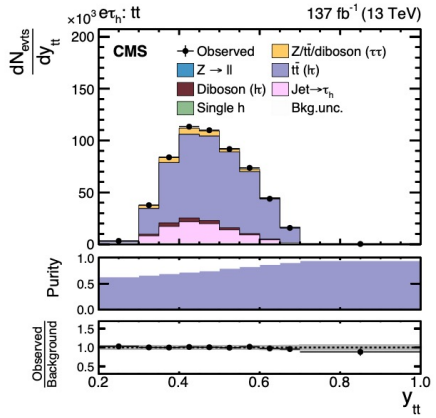
JHEP11(2021)057

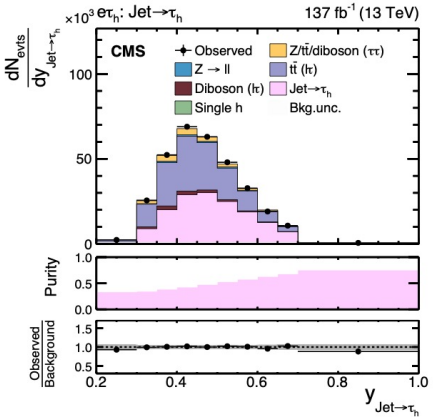
- CMS has a very recent publication (Nov. 9) searching for H → h + h_s with full Run 2 data. (H: heavy Higgs. h: the SM 125 GeV Higgs. h_s: another Higgs boson.)
- Searches performed in h→ττ, h_s→bb final state. At least one τ deca hadronically.
- Events sorted into 5 categories based on multiclass NN outputs (1 signal node, 4 background nodes), for each data-taking year and each final state (45 in total).

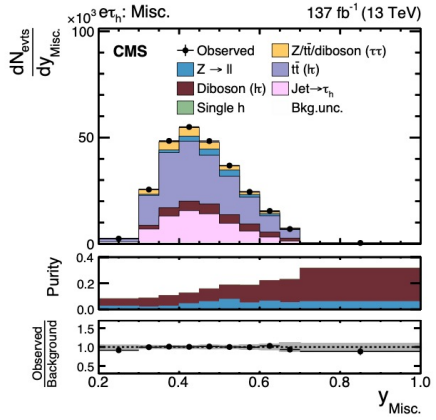


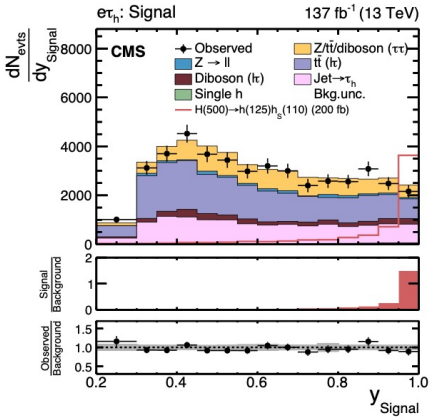










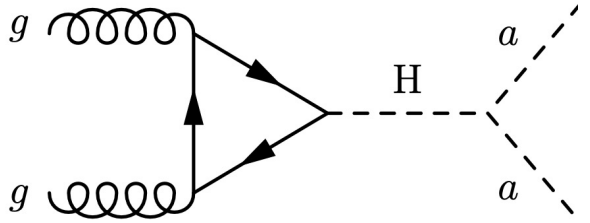


Using Higgs to Search for Light Resonances

* Current constraint from ATLAS and CMS on the H → invisible/undetected decays are at 20 to 30% level (partial data), allow large phase space to search for H → BSM light states.
* Both ATLAS and CMS have searched those light resonances in many different channels.

Searches for H → aa

arXiv:2110.00313
CMS-PAS-HIG-21-003

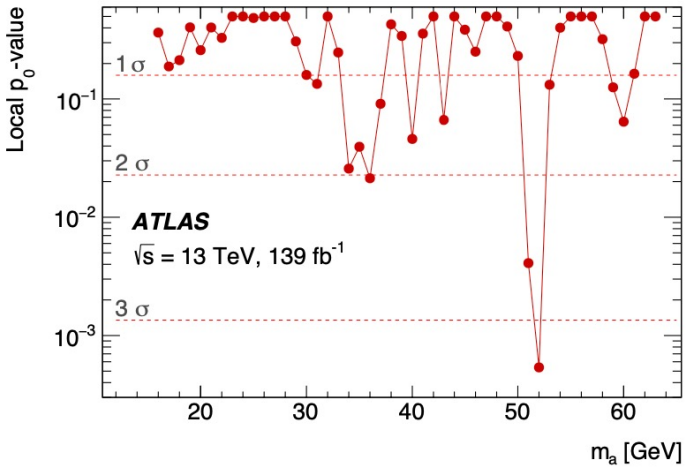


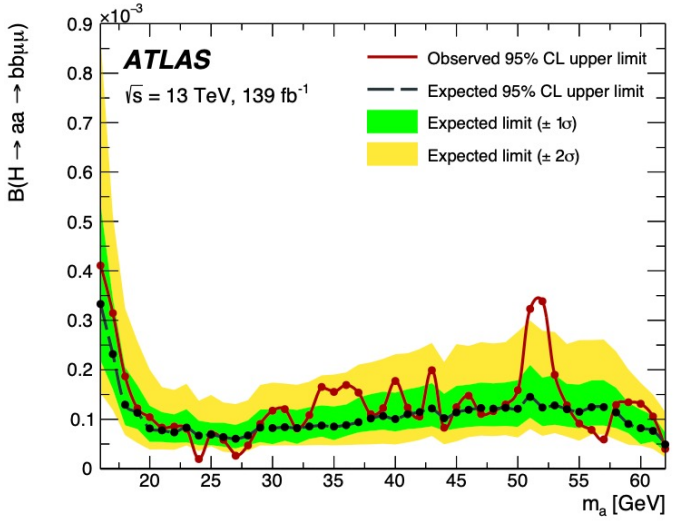
a is pseudoscalar particle

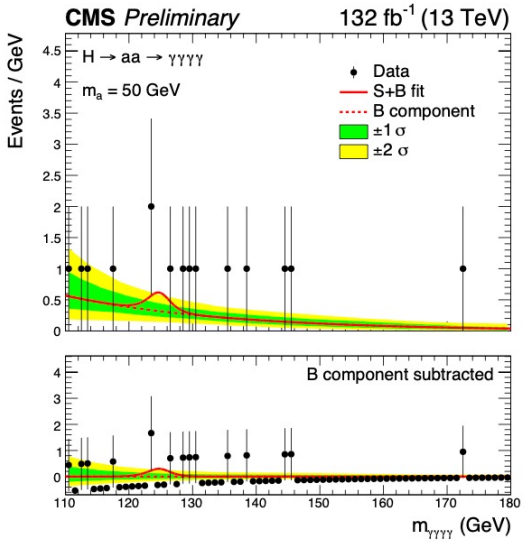
- A recent update in bbμμ channel from ATLAS
- Full Run 2 data
- Kinematic likelihood (KL) fit is performed exploiting equal invariant masses of bb and μμ
- $m_{\mu\mu}$ used to constrain m_{bb}

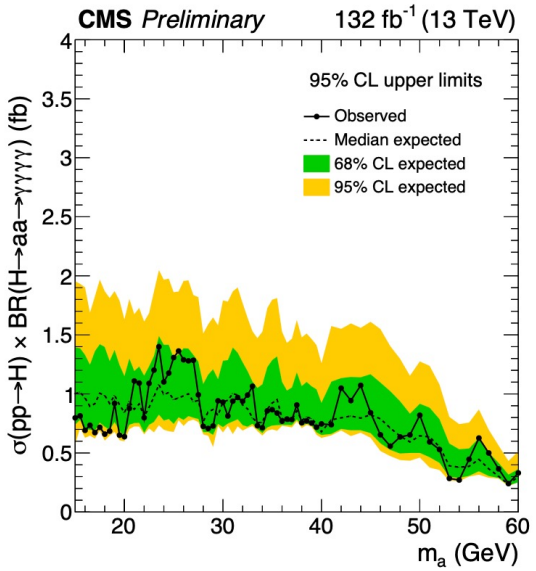
- A recent update in γγγγ channel from CMS
- Full Run 2 data
- Primary vertex selected based on BDT (instead of sum pT squared) → 3% improvement of the resolution of the invariant mass
- Event mixing used for background estimates

global: 1.7σ



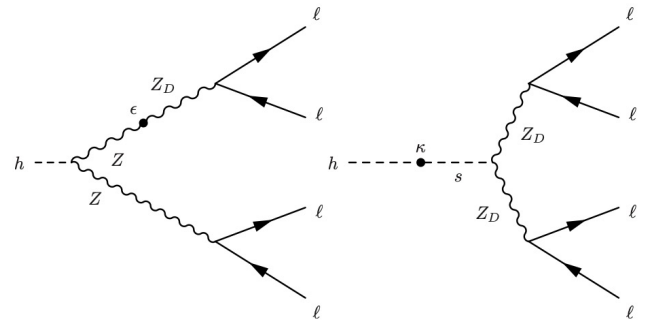






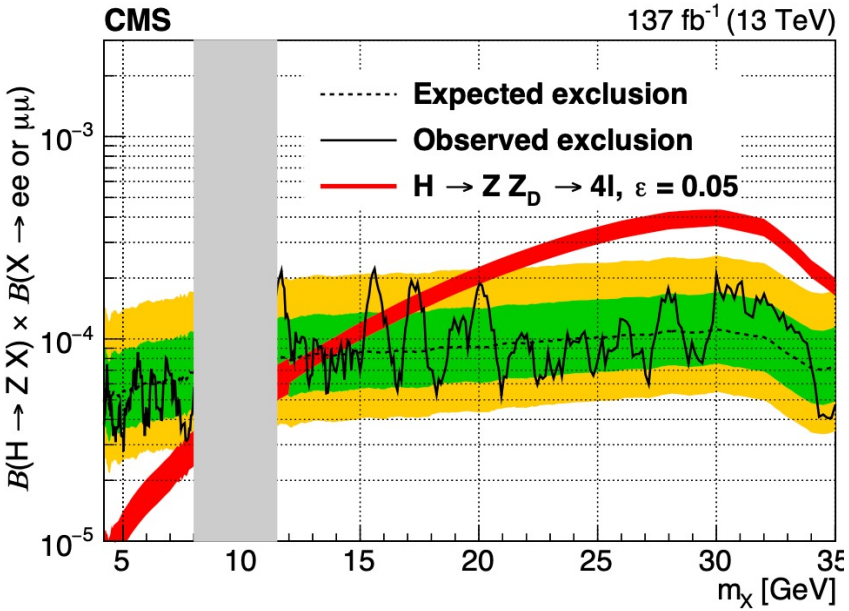
arXiv:2111.01299

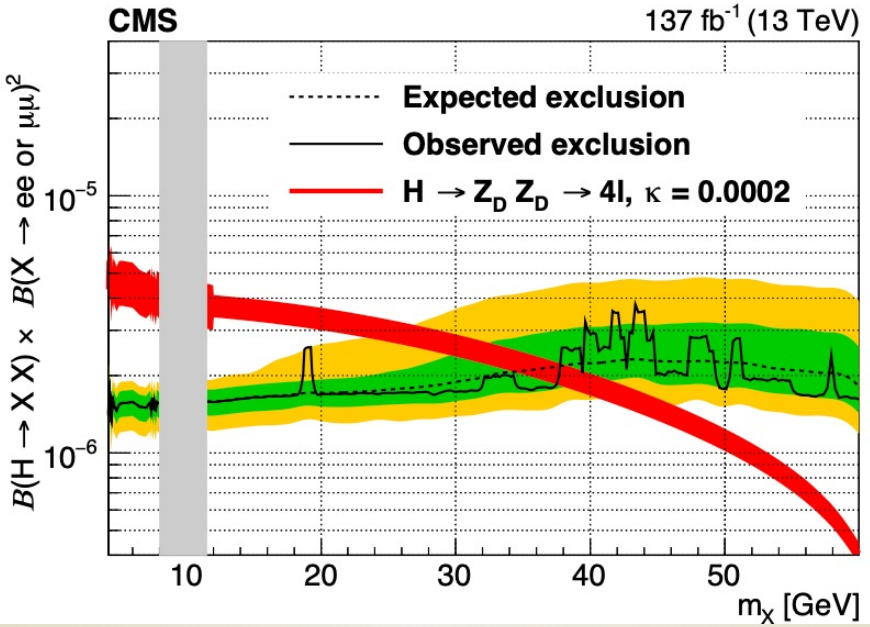
Search for H → ZX/XX in 4l Final State

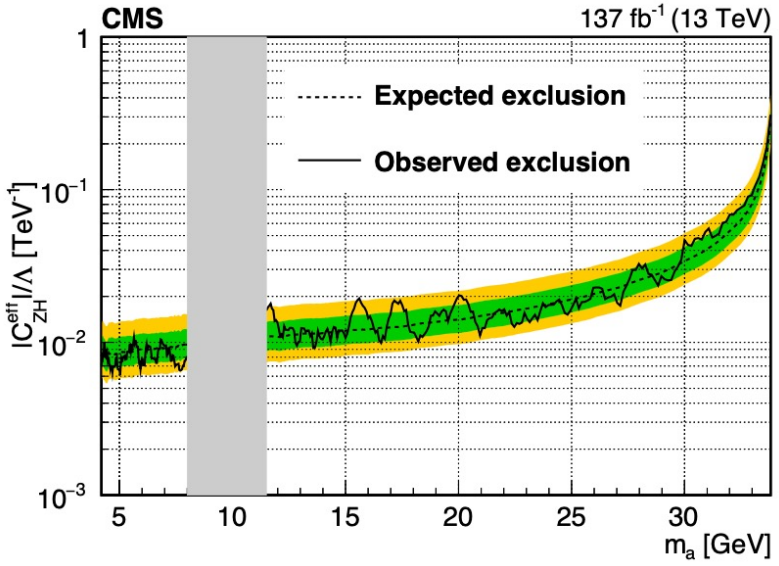


* Recent update from CMS with full Run 2 data. Two models considered
  * The hidden Abelian Higgs Model (HAHM). Interactions of the dark sector and SM particles through the kinetic-mixing or Higgs-mixing
  * The axion-like particles (ALPs) (formulated as an EFT model) → particularly motivated by the observed muon magnetic moment anomaly
* Different dilepton mass requirements in ZX and XX selections

Relevant Wilson coefficients
C_{ZH}/Λ: H→Za
C_{aH}/Λ^2: H→aa

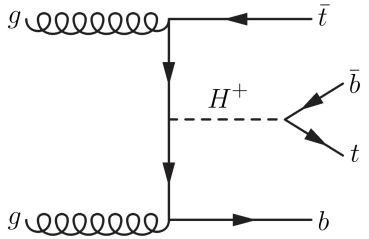






Searches for Charged Higgs

- Both ATLAS and CMS have a wide range of searches for charged Higgs.
- Charged Higgs to fermions: below top mass and above top mass
- Charged Higgs to bosons



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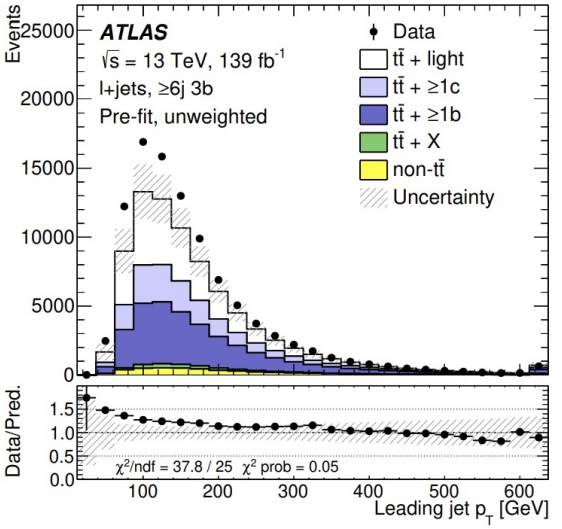
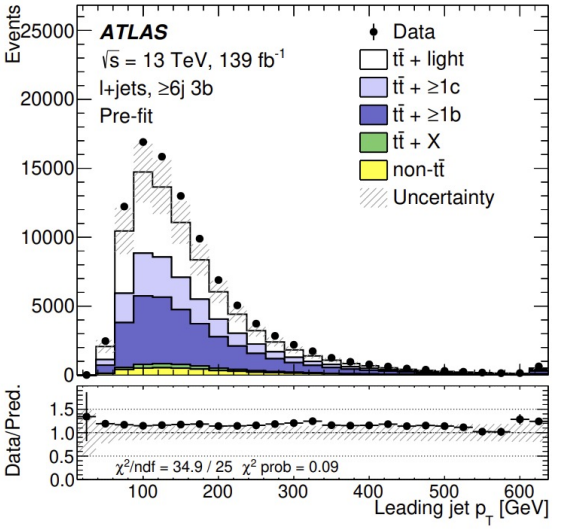
Charged Higgs to tb

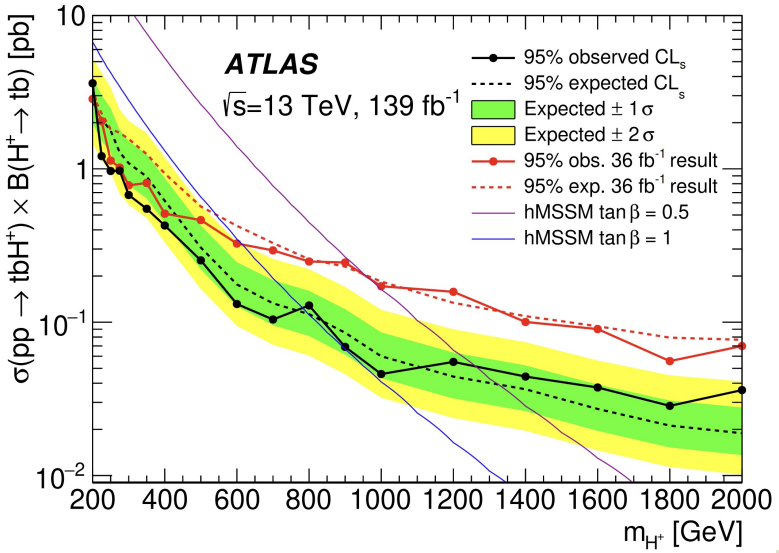
- Recent results from ATLAS searching for charged Higgs to tb, in the top and b associated production with full Run 2 data
- One electron/muon is required.
- Events split into different regions based on number of jets and b-tagged jets
- Reweighting factors derived from #bjet = 2 regions applied to high #bjet signal regions
- MVA used to further separate signal and background. NN output as final discriminator

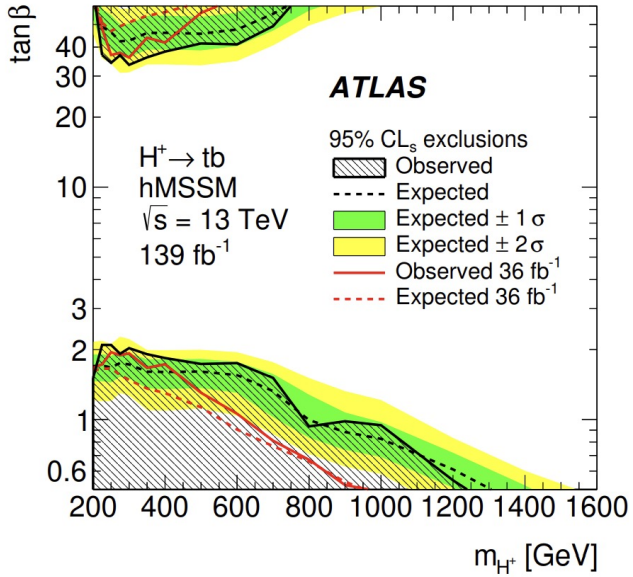


(c) ≥6j3b, unweighted.

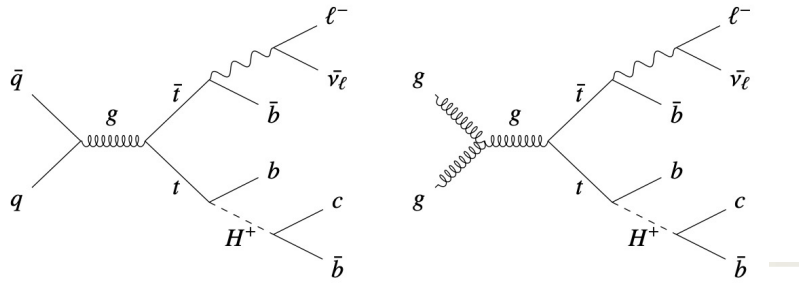


(g) ≥6j3b, reweighted.





Charged Higgs to cs/cb



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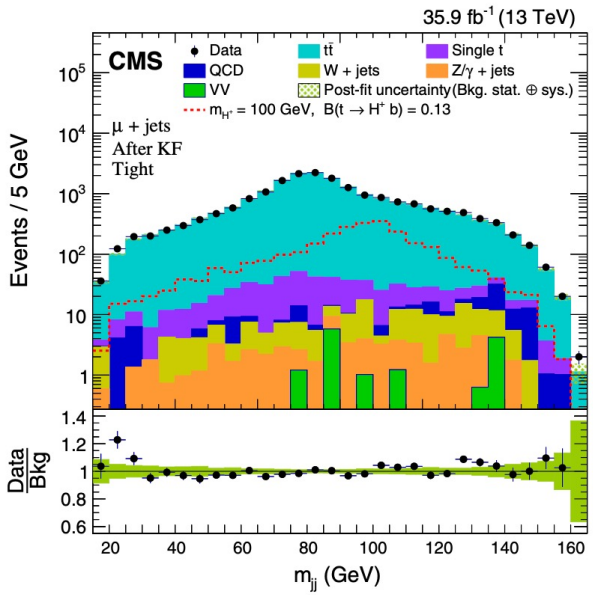
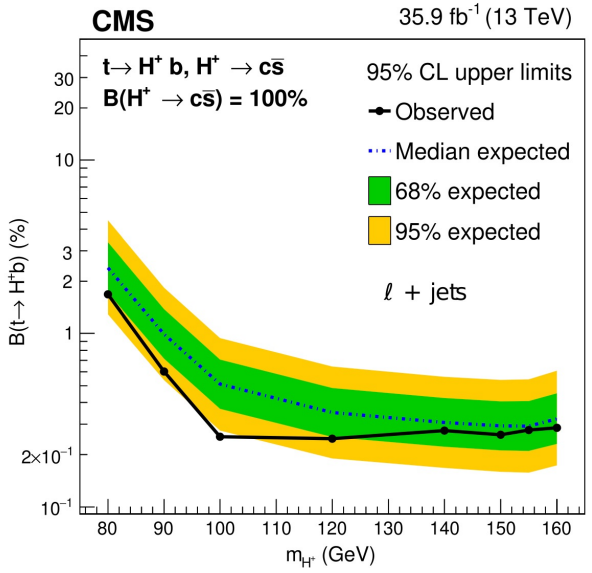
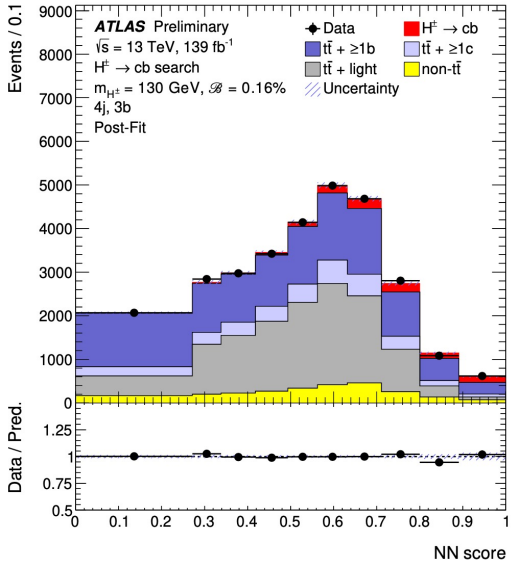
- Targeting at lower mass region below top mass
- Using ttbar events and charged Higgs from top decay, which then decays to light quarks
- The other top decays leptonically

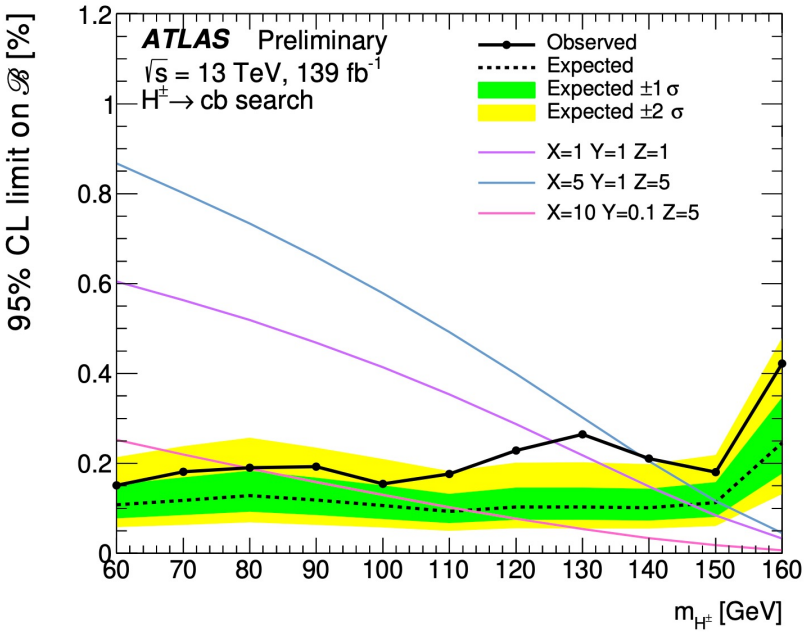
CMS searched in cs channel with 35.9 fb^{-1} data
Results obtained by fitting over m_{jj} after kinematic-fit





ATLAS recently reported results in cb channel with full Run 2 data
NN used to further separate signal and background





Theoretical lines refer to 3HDM model

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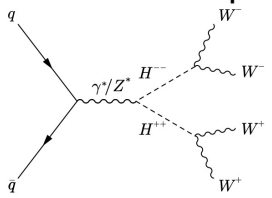
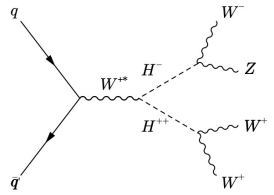
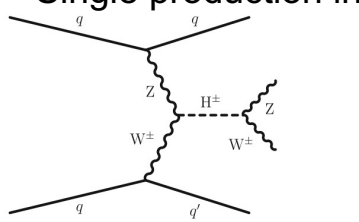
Charged Higgs to WZ/WW

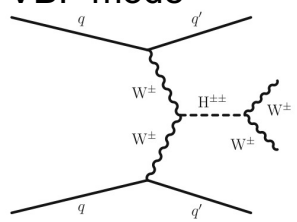
Pair production





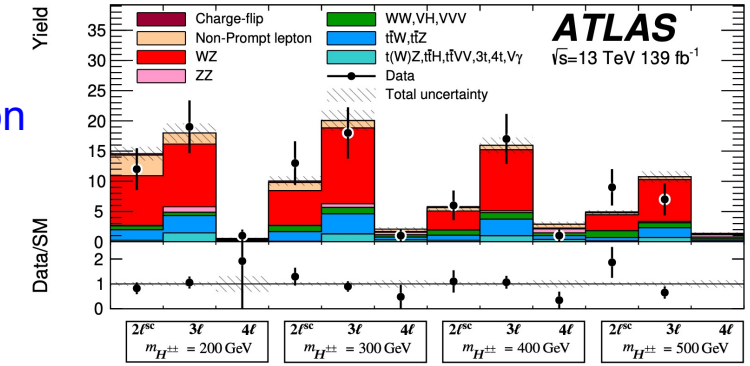
Single production in VBF mode

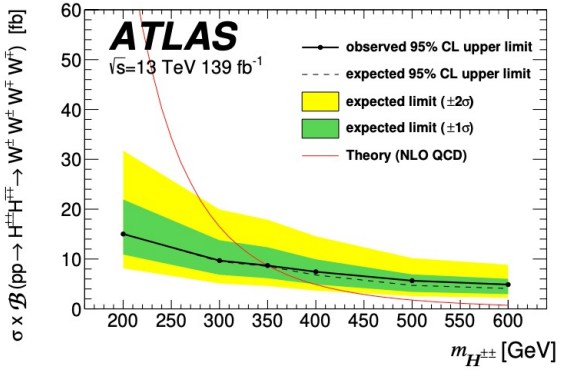


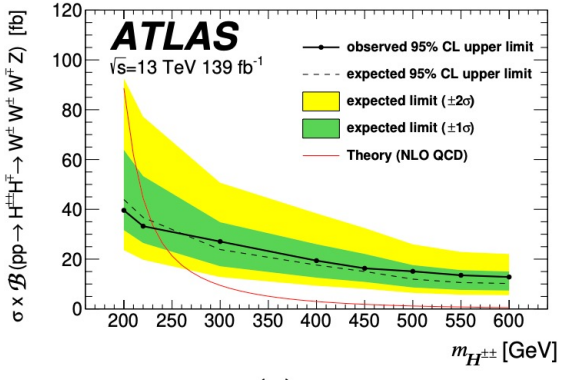


- ATLAS and CMS also searched charged Higgs (H^+, H^{++}) in the WW/WZ channel
- Recent updates from ATLAS focusing on the pair production, and CMS focusing on the single production with full Run 2 data

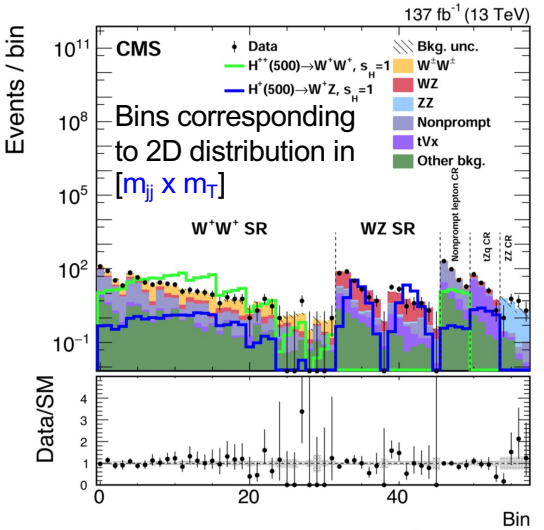
ATLAS search performed in multilepton final state

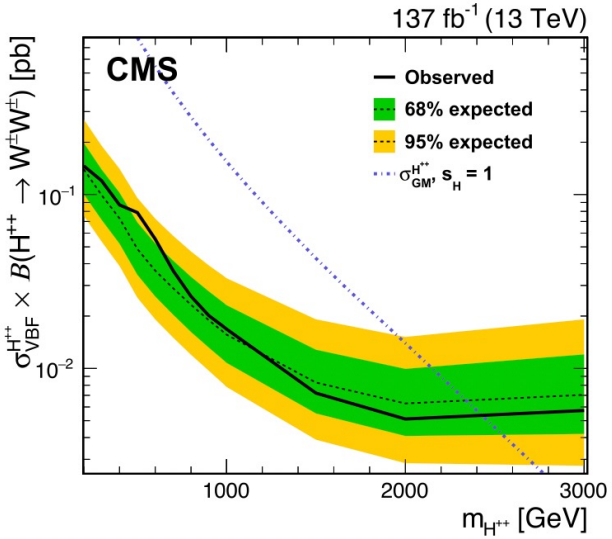


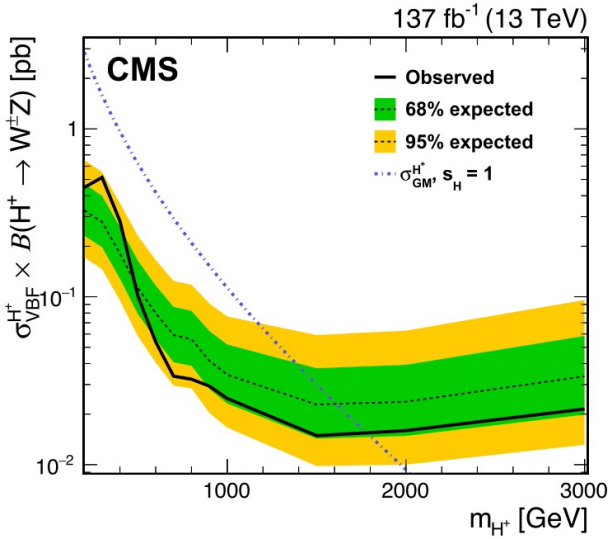




CMS search targets at VBF mode by requiring two tag jets with large invariant mass and rapidity separation

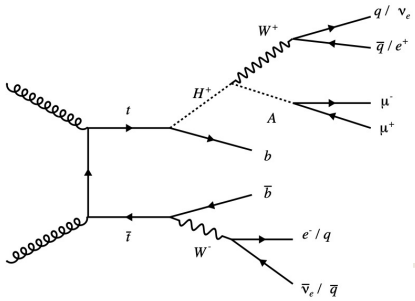




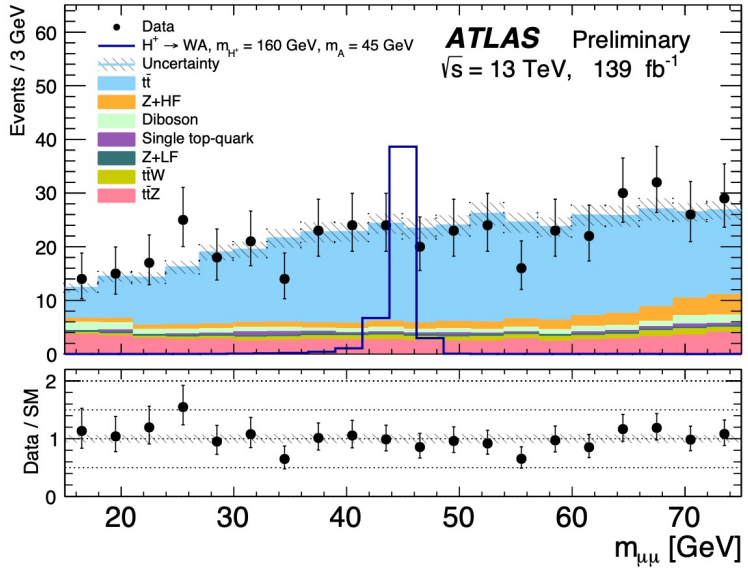


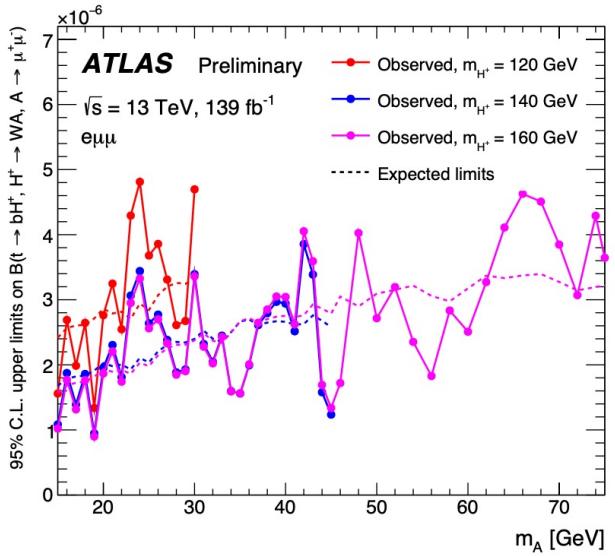
Charged Higgs to WA

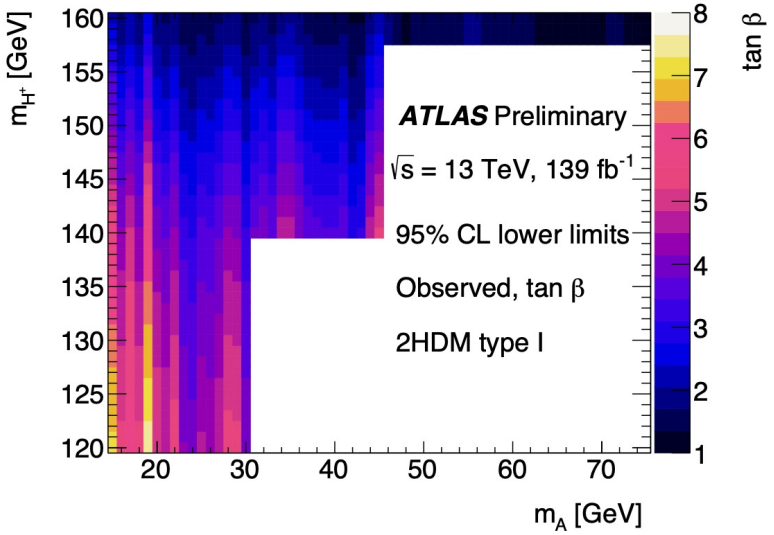
ATLAS-CONF-2021-047



- ATLAS reports search for $H^+ \rightarrow WA$ (A is pseudoscalar) using ttbar events with full Run 2 data
- Target at low mass region. The fermion channel can be strongly suppressed.
- Events required to have one electron and two muons. Two muons from A decay.



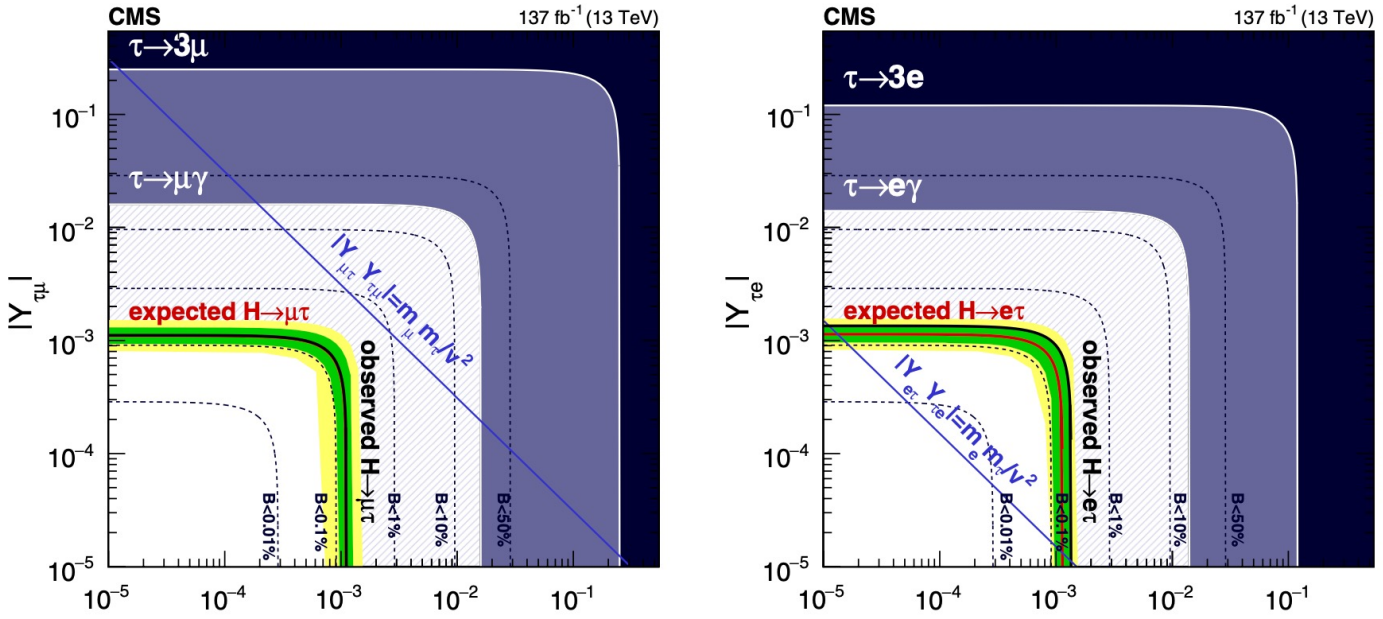




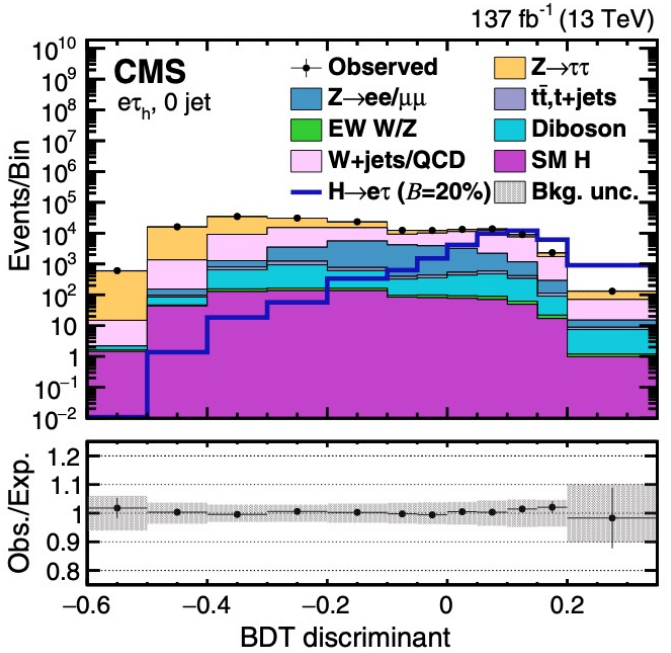
Searches for LFV using Higgs

Phys. Rev. D 104 (2021) 032013

- Recent results from CMS using full Run 2 data, searching for lepton-flavor violation (LFV) in Higgs decays.
- Analysis performed in μτ and eτ channels, where τ decays either hadronically, or leptonically (but not in ee or μμ final state)
- BDT trained in each channel



$|Y_{\mu\tau}|$ Limits on LFV Yukawa couplings $|Y_{e\tau}|$



Observed (expected) upper limits

$$\mathcal{B}(H \to \mu\tau) < 0.15(0.15)\%$$

$$\mathcal{B}(H \to e\tau) < 0.22(0.16)\%$$

Uncertainty dominant by

- ✓ Bin-by-bin uncertainty
- ✓ Mis-identified lepton kinematic distributions

Summary

- Both ATLAS and CMS have established wide range of searches using the discovered 125 GeV Higgs boson
  - Continue looking for SM Higgs in the rare decay modes
  - Looking for BSM Higgs
  - Using SM Higgs to search for BSM particles
  - …
- Still several Run 2 analyses ongoing with full luminosity
- Run 3 is coming. Stay tuned.

backup