Search for BSM/Rare Higgs at the LHC

Yanlin Liu (刘彦麟)
Shandong University
On behalf of ATLAS and CMS

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Higgs Discovery on July 4th 2012

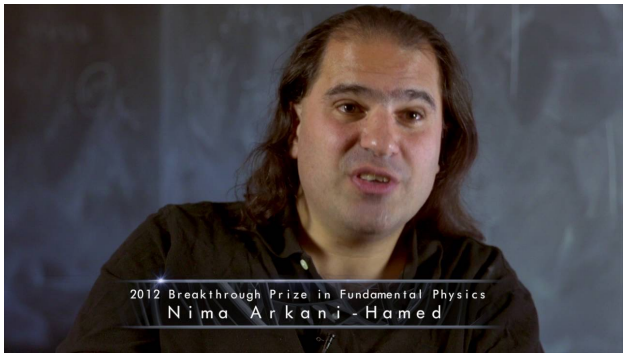
It Is Not the End…

Higgs is Really New Physics!

* We've never seen anything like it
* Harbinger of Profound New Principles at work in quantum vacuum

PUT IT UNDER MICROSCOPE

STUDY IT TO DEATH



From Nima Arkani-Hamed

Many Open Questions about the Higgs

- Are the properties and couplings of the Higgs consistent with the SM prediction?
- What are its mass, width, rate, etc?
- How to access the structure of the Higgs potential?
- Can we probe the rare Higgs boson decay? Does it decay to any final states not predicted by the SM ?
- Does additional low/high-mass BSM Higgs boson (namely additional scale field) exist?
- …

Xiaohu's talk

Nan's talk

What I will cover today

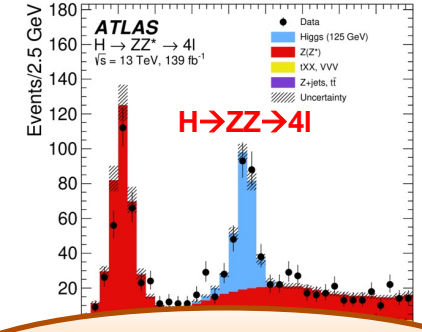
Analysis Topics Covered Today

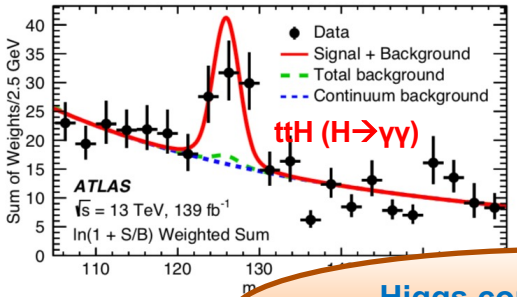
- Rare Higgs boson decays: H→μμ, H→cc, H→ee, H→Zγ
- Search for exotic decay of the SM Higgs boson: H→aa→4γ, H→Za→ll$\gamma\gamma$, H→aa→bbμμ
- Search for additional neutral/charged Higgs bosons: low mass X→$\gamma\gamma$, heavy mass X→HH/YH, H^+→WZ

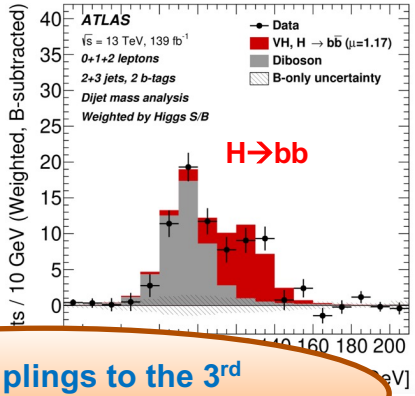
Disclaimer: it is likely the selected topics are towards my personal taste, apologize for this!

Search for Rare Higgs Boson Decays

H→μμ: Why It's Important?

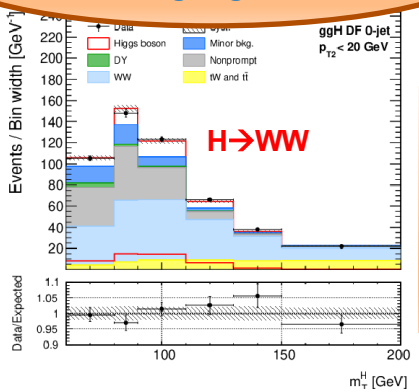




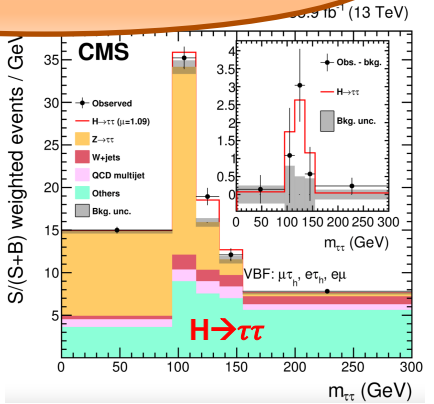


Higgs coupling to massive gauge bosons

Higgs couplings to the 3rd generation fermions

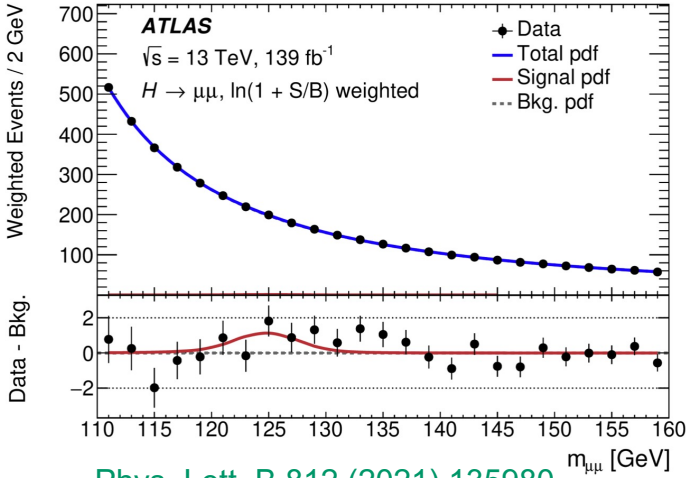


One of the next big milestones:
Higgs couplings to the 2nd generation fermions
H→μμ is the most promising channel to export this

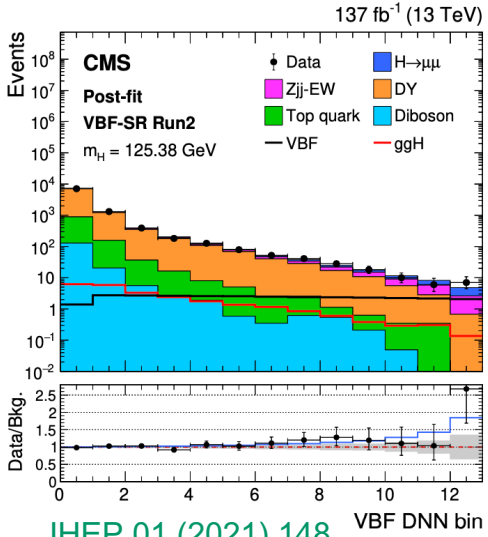


H→μμ: Analysis Strategy

- Signatures: 2 isolated muons with opposite charge
- Major challenge: low BR and large irreducible background from Drell-Yan
- MVA-based categorization driven by four major Higgs production modes
- Signal extraction: generally analytic function fit to $m_{\mu\mu}$ spectra (N.B.: template fit to MVA in VBF category in CMS)



Phys. Lett. B 812 (2021) 135980



JHEP 01 (2021) 148

H→μμ: Run 2 Results

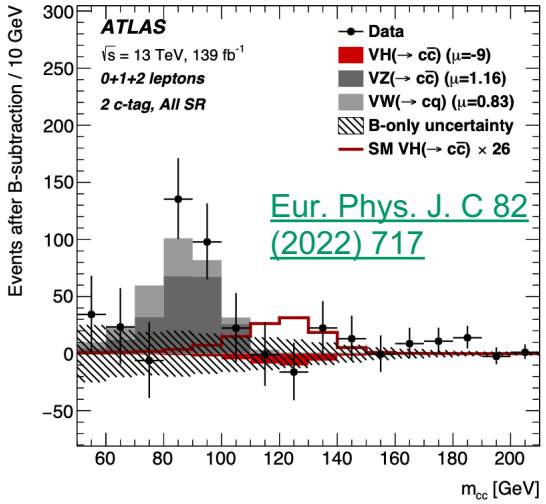
- ATLAS: measured μ = $1.17 \pm 0.58(stat)^{+0.18}_{-0.13}(sys)$, obs. (exp.) significance is 2.0 (1.7) σ
- CMS: measured μ = $1.19^{+0.40}_{-0.39}(stat)^{+0.15}_{-0.14}(sys)$, obs. (exp.) significance is 3.0 (2.5) σ
- Both analyses are statistical uncertainty dominated currently

CERN experiments announce first indications of a rare Higgs boson process

The ATLAS and CMS experiments at CERN have announced new results which show that the Higgs boson decays into two muons

H→cc: VH Analyses

- Direct probe of Higgs coupling to the charm quark
- Target leptonic decay of W/Z bosons, major bkg.: W/Z+HF, ttbar
- Both ATLAS and CMS used novel c-tagging techniques



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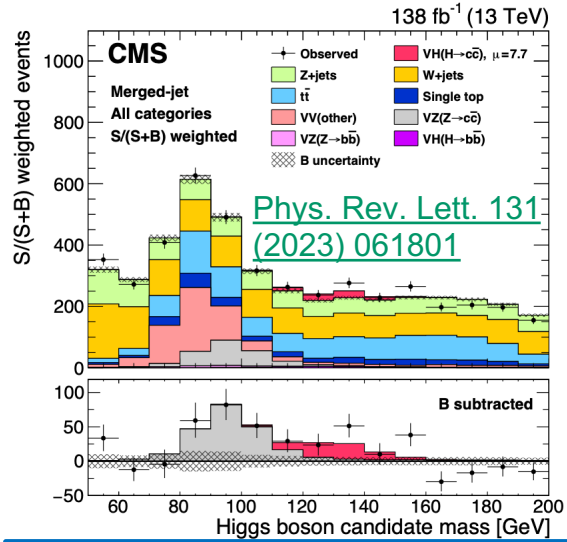
Obs.(exp.) limit on μ: 26 (31)
$|\kappa_c| < 8.5$ (12.4)

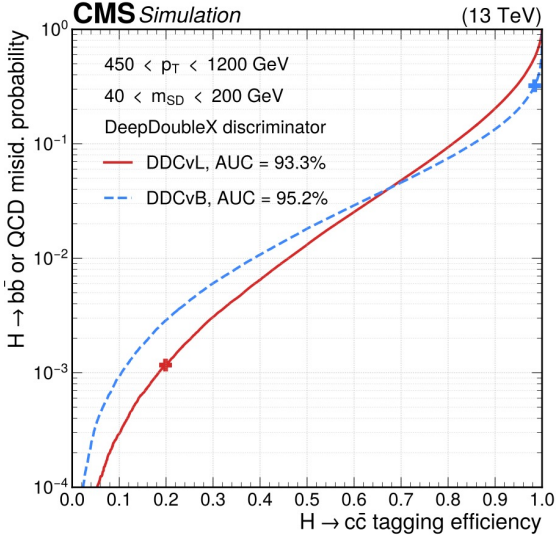


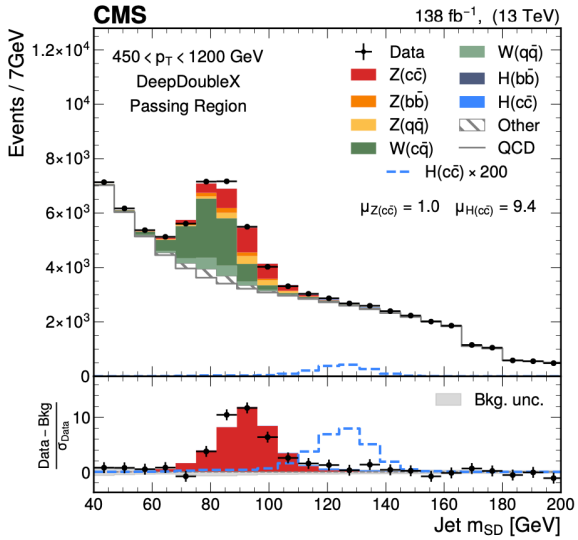
Phys. Rev. Lett. 131 (2023) 061801

Obs.(exp.) limit on μ: 14 (7.6)
$1.1 < |\kappa_c| < 5.5$ ($|\kappa_c| < 3.4$)

H→cc: Boosted Analysis

- Probe of $p_{T,H} > 450$ GeV phase space (enriched in ggF production) in H→cc channel by CMS
- Higgs reconstructed as a large-R jet with DNN-based algorithm
- Major bkg. coming from multi-jet



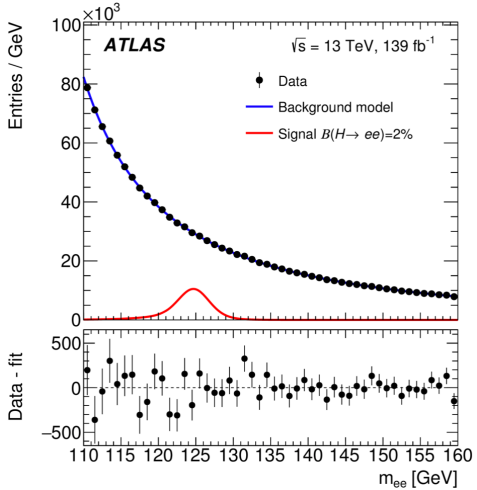


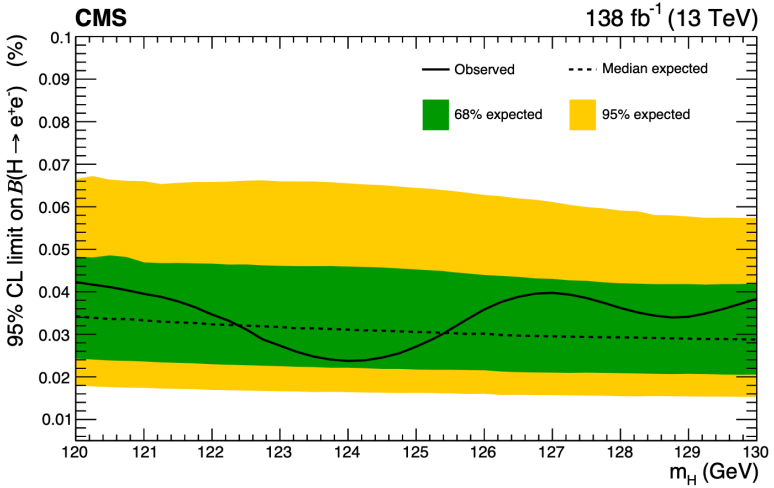
Obs.(exp.) limit on μ: 47 (39)

Phys. Rev. Lett. 131 (2023) 041801

H→ee

- Yukawa coupling to the 1st generation fermions, very low BR: ~5×10^{-9}
- Categorization optimized for ggF and VBF production modes
- A simultaneous fit to m_{ee} spectra across the categories with analytic functions





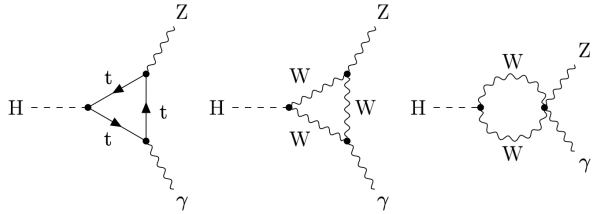
Obs.(exp.) limit on BR: 3.6×10^{-4} (3.5×10^{-4})

Phys. Lett. B 801 (2020) 135148

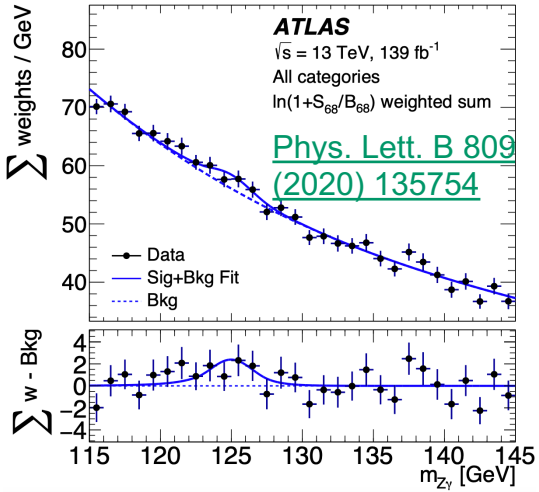
Obs.(exp.) limit on BR: 3.0×10^{-4}

Phys. Lett. B 846 (2023) 137783

H→Zγ



- In SM, BR is 1.54×10^{-3}, sensitive to BSM physics entering loop corrections; signal signature: Z→ee/μμ + 1 photon
- Selected events categorized to exploit four major production modes
- Simultaneous fit to $m_{ll\gamma}$ spectra across the categories to extract signal



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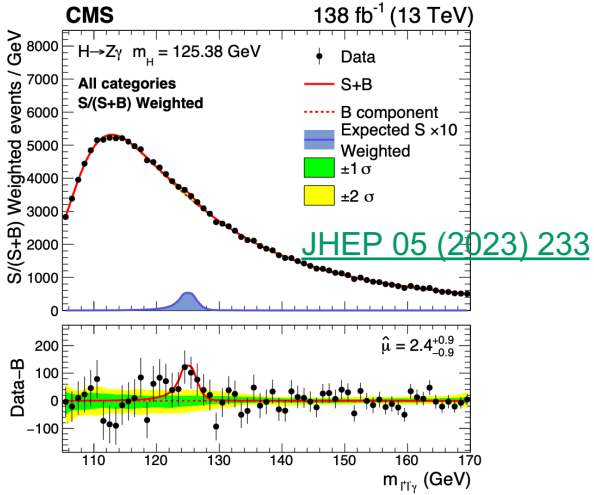

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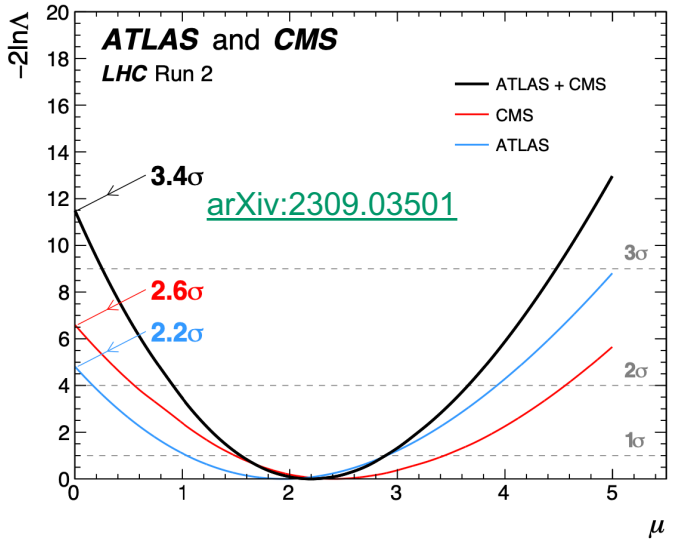
Obs.(exp.) significance: 2.2 (1.2)σ

Obs.(exp.) significance: 2.7 (1.2)σ

H→Zγ: ATLAS+CMS Combination

- Performed statistical combination between the two experiments
- Uncertainties are treated uncorrelated except for sys. associated with the missing high order of ggF XS and H→Zγ BR predictions

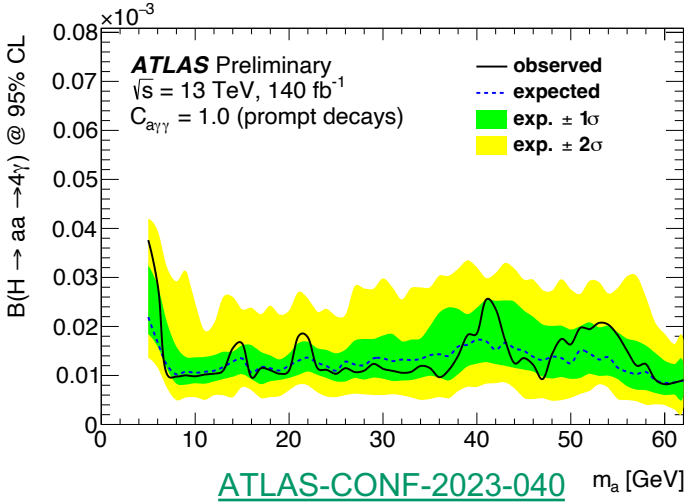


Obs.(exp.) significance: 3.4 (1.6)σ, evidence for this process
The results agree with the SM prediction within 1.9σ

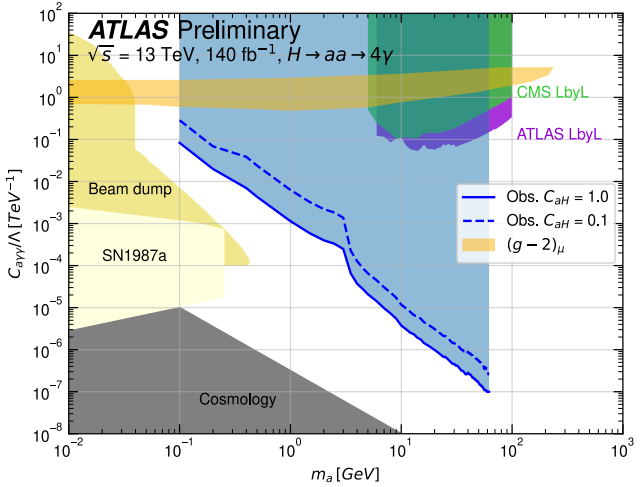
Search for Exotic Decay of the SM Higgs Boson

Search for H→aa→4γ at ATLAS

- Axion-like particles (ALPs) decaying into $\gamma\gamma$ is sensitive to various models that could explain $(g\text{-}2)_\mu$ discrepancy
- Signal signature depending on the axion mass (collimated/resolved photons) and $C_{a\gamma\gamma}$ (long-lived/promptly decaying)
- m_{inv}^{reco} (invariant mass of all photon candidates) used for final fitting

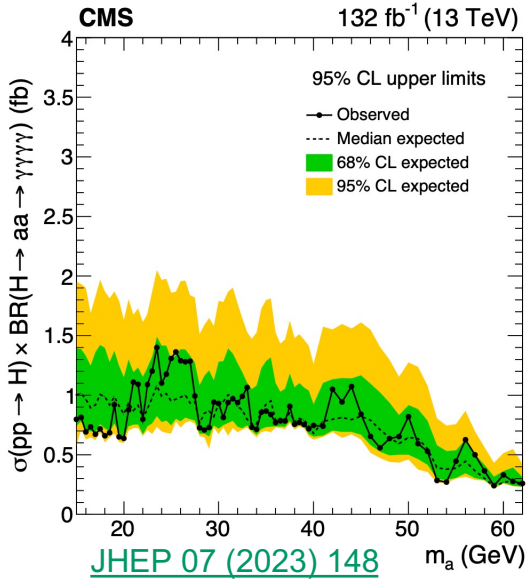


ATLAS-CONF-2023-040



Search for H→aa→4γ at CMS

- Target a with mass > 15 GeV
- Signature: 4 isolated photons
- BDT trained to separate sig. and bkg.



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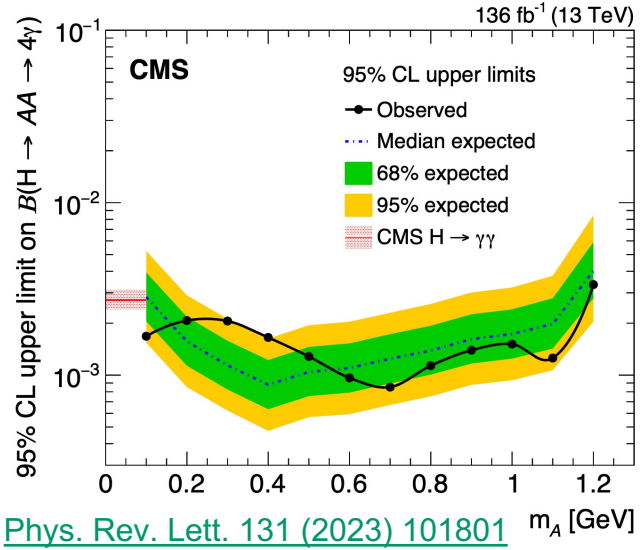
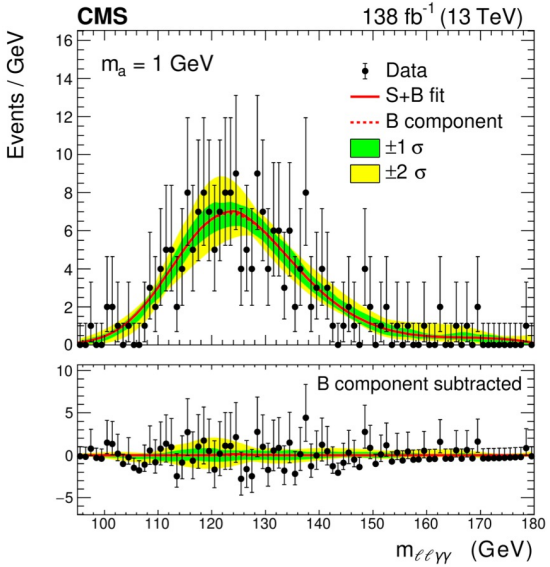
- Target A with mass 0.1-1.2 GeV
- DNN-based algorithm used to reconstruct two boosted γ as a single photon-like object



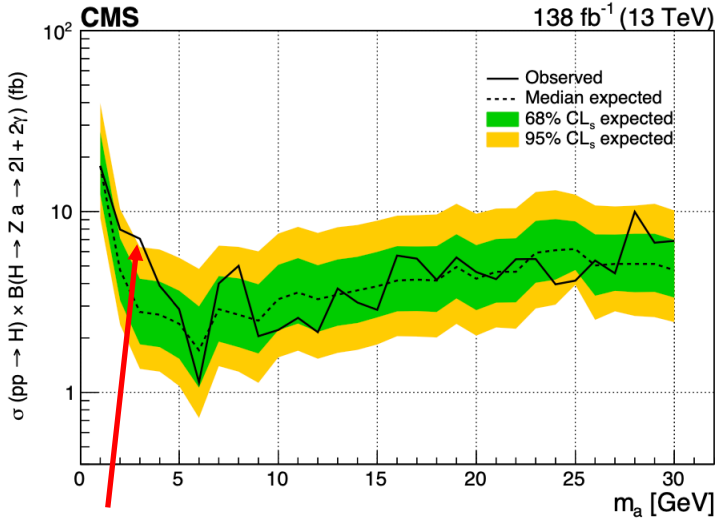
Phys. Rev. Lett. 131 (2023) 101801

H→Za→llγγ

- Target m_a range from 1 to 30 GeV, Z is on-shell
- Dominant background coming from Z+jets (where jets → fake photons)
- BDT trained to separate sig. from bkg., used to categorize events



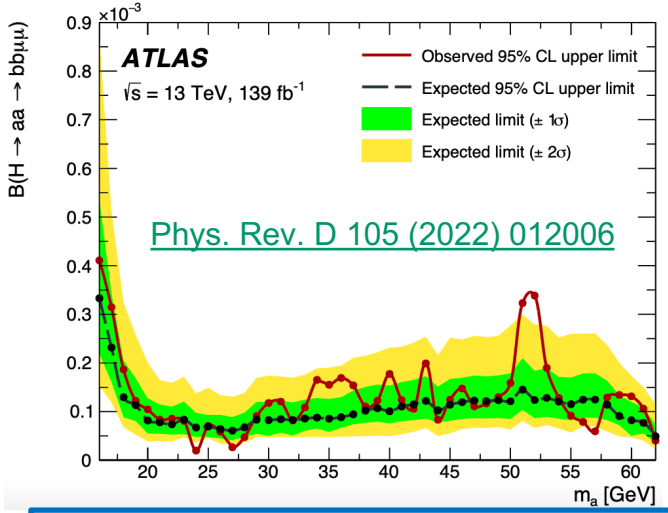
arXiv:2311.00130

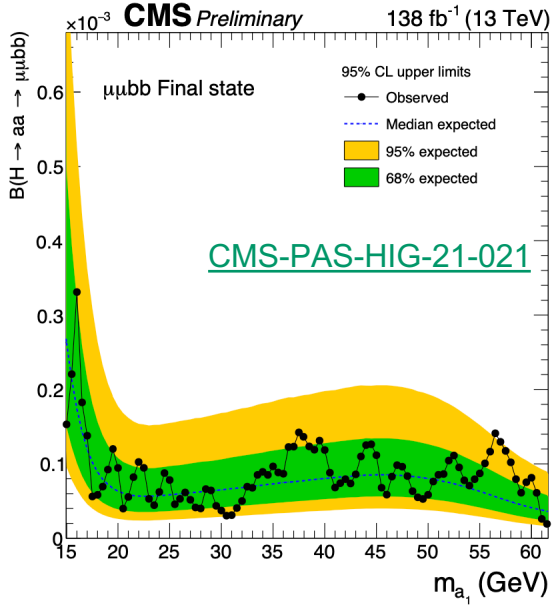


Local (global) significance for 3 GeV is 2.6 (1.3)σ

Search for H→aa→bbμμ

- Events selected with single/di-muon triggers, $m_{\mu\mu}$ in 15 – 65 GeV
- Performed kinematic likelihood fit exploiting equal m_{bb} and $m_{\mu\mu}$ to improve mass resolution and reduce bkg.
- BDT trained to separate sig. from SM bkg. (DY+jets, ttbar)



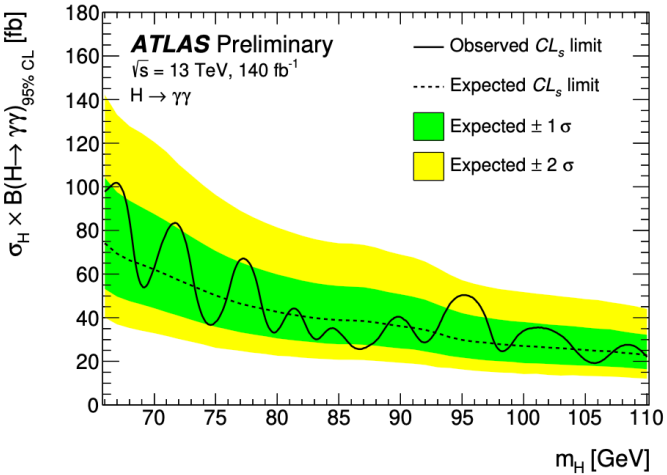


Local (global) significance for 52 GeV is 3.3 (1.7)σ

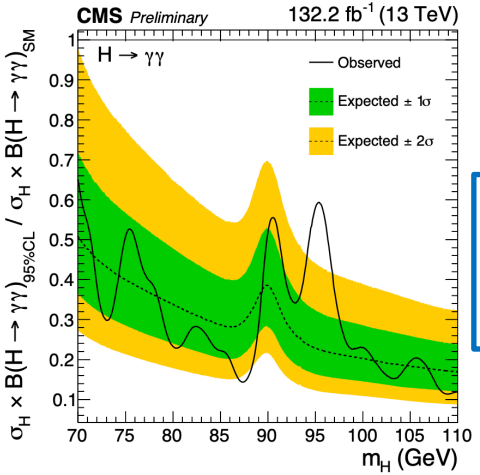
Search for Additional Neutral/Charged Higgs Boson

Search for Low-mass H→$\gamma\gamma$

- Searching for mass range within ~70 - 110 GeV
- Signature: two isolated γ; Z->ee bkg. largely reduced via object BDT
- Events categorized based on photon conversion and BDTs
- Analytic function fit to the observed $m_{\gamma\gamma}$ spectra (~65 - 120 GeV)
  - ➢ Allow data on either side of hypothetical signal peak to constrain bkg.



ATLAS-CONF-2023-035

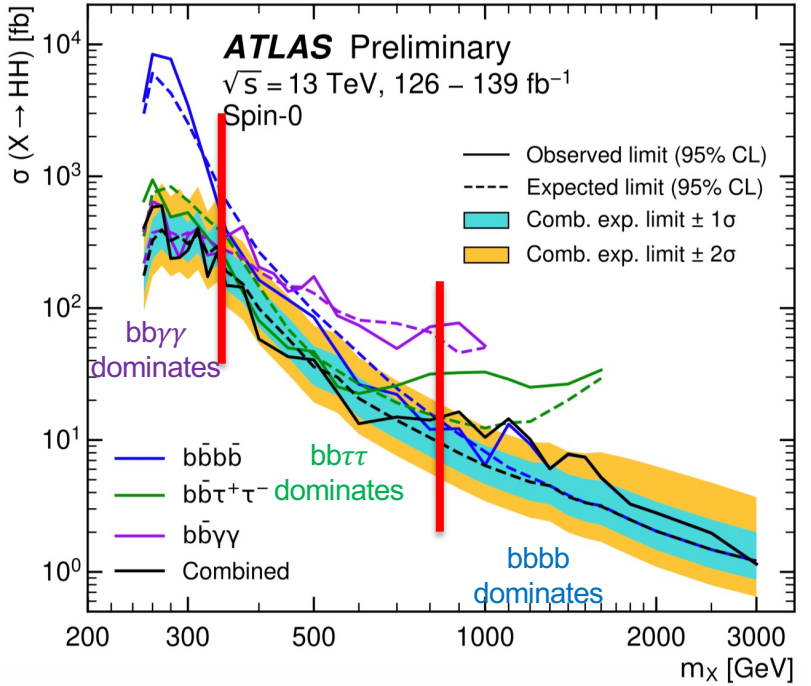


CMS-PAS-HIG-20-002

Local (global) significance for 95.4 GeV is 2.9 (1.3)σ

Search for X→HH at ATLAS

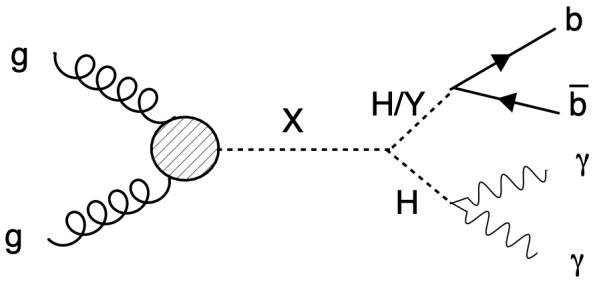
- Many BSM theories predicted a heavy scalar (X) decaying into two SM Higgs bosons
- Three major sensitive channels for HH: bb$\tau\tau$, 4b and bb$\gamma\gamma$
- Performed statistical combination for the three channels to maximize the sensitivity



ATLAS-CONF-2021-052

Largest excess at 1.1 TeV: local (global) significance is 3.2σ (2.1σ)

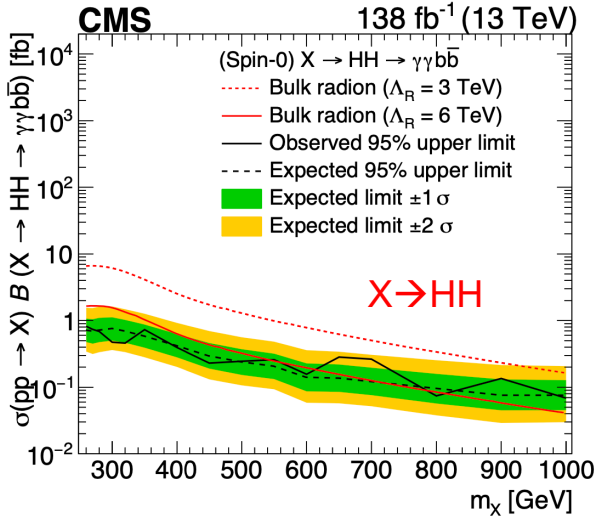
Search for X→HH/YH→bb$\gamma\gamma$

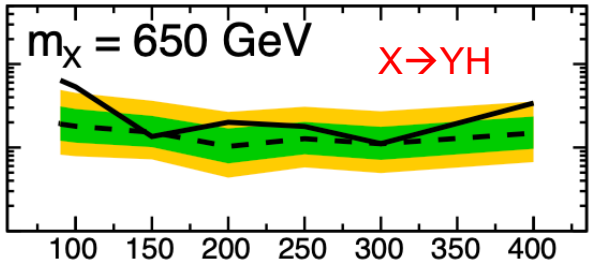


- Signature: 2 isolated γ, 2 b-jet
- $\widetilde{M}_X$ used to improve the the resolution

$$\widetilde{M}_X \equiv m_{\gamma\gamma jj} - (m_{\gamma\gamma} - m_H) - (m_{jj} - m_{H \text{ or } Y})$$

- BDT trained to separate sig. from $\gamma\gamma$/γ+jets bkg.
- Event categorized based on BDT and $\widetilde{M}_X$

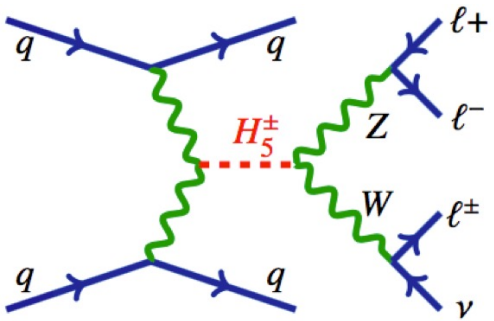




arXiv:2310.01643

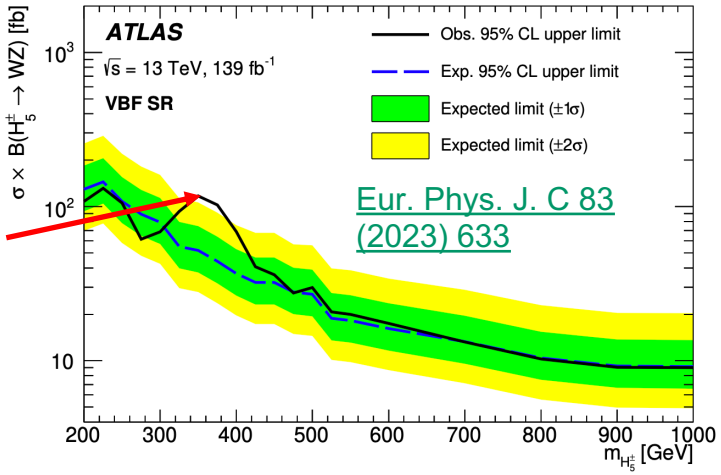
Local (global) significance for m_X = 650 GeV, m_Y = 90 GeV is 3.8 (2.8)σ

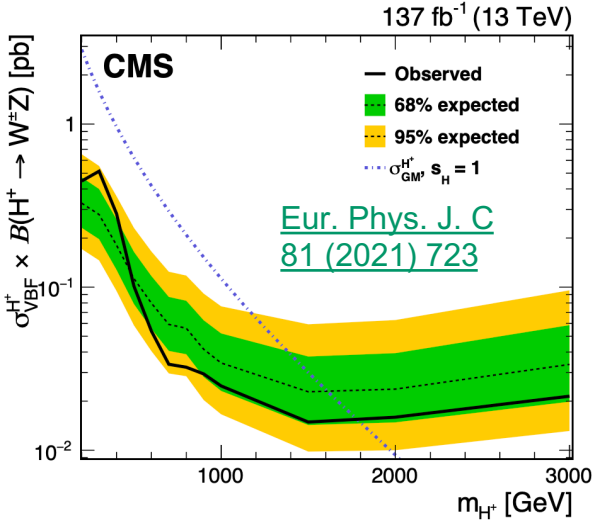
Search for Charged Higgs Decaying into WZ



- Predicted by Georgi–Machacek (GM) model, VBF mode
- Events selected with 3 leptons and 2 forward jets
- ATLAS: MVA used for sig. and bkg. (WZ, ZZ, etc) classification; m_{WZ} used for final fitting
- CMS: 2-D fit with m_T^{WZ} and m_{jj}

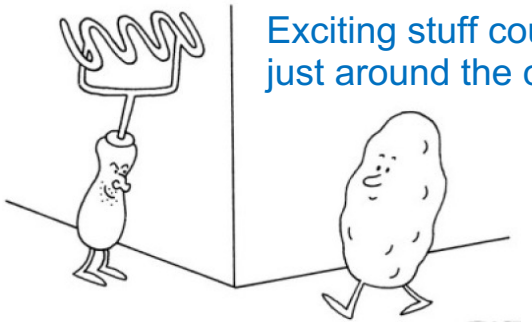
Local (global) significance for 375 GeV is 2.8 (1.6)σ

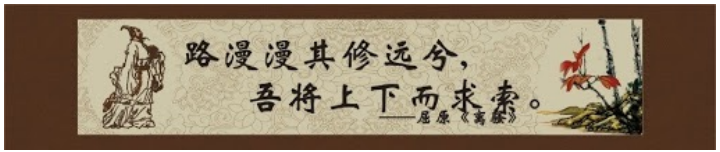




Summary

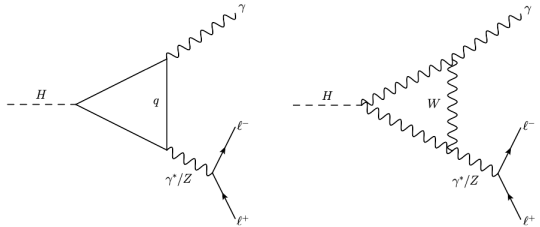
- Presented the latest searches for Higgs boson rare decay at ATLAS and CMS: first evidence for H→μμ and H→Zγ
- Searches for exotic decay of SM Higgs, as well as additional neutral/charged Higgs are also presented: no sign of new physics in the Higgs sector, stringent limits have been set according to relevant models
- Large amount for Run 3/HL-LHC data can provide us room for more precise probe, stay tuned!



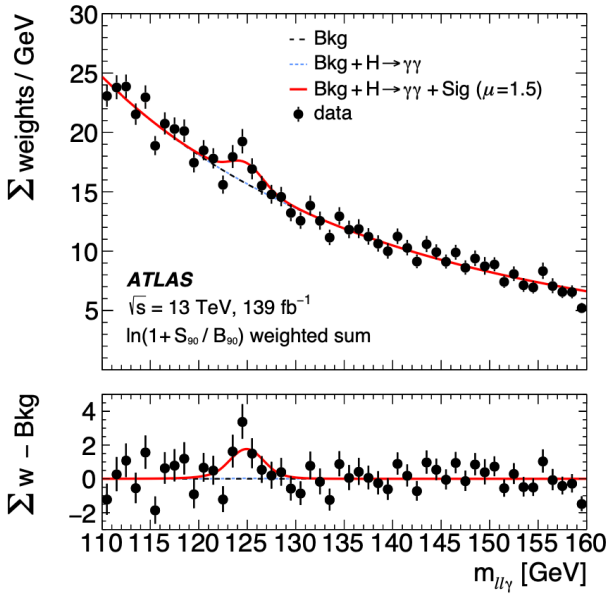


Backup

H→γ*γ→llγ



- Sensitive to new physics as well as CP-violation effect in the Higgs sector
- m_{ll} < 30 GeV, orthogonal to H→Zγ phase space
- Dedicated electron ID for collimated signatures
- Three channel: μμγ, eeγ merged, eeγ resolved
- Categories based on lepton flavor and topologies
- Analytic function fit to the $m_{ll\gamma}$ spectra

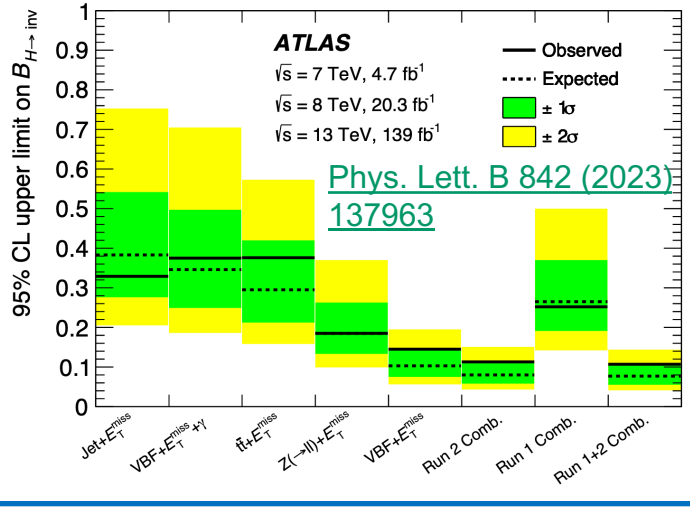


The measured μ = 1.5 ± 0.5
Obs.(exp.) significance: 3.2 (2.1)σ,
evidence of this rare decay

Phys. Lett. B 819 (2021) 136412

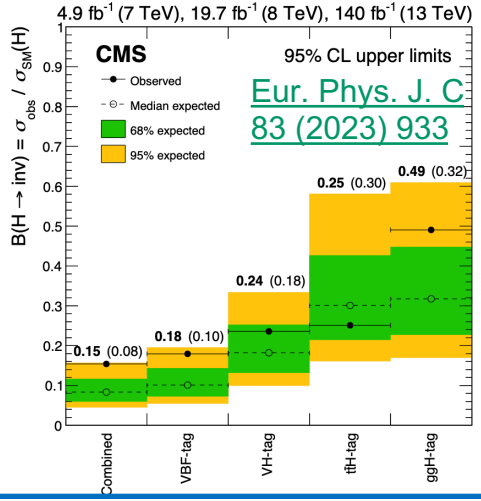
H→Invisible

- In SM, H→inv is only possible via H→ZZ*→4ν with BR of 0.1%
- BR is sensitive to Higgs decaying dark matter particles in BSM scenarios
- Signature: Higgs decay products manifest as large MET
- Exploited four major production modes (VBF dominate the sensitivity)



Phys. Lett. B 842 (2023) 137963

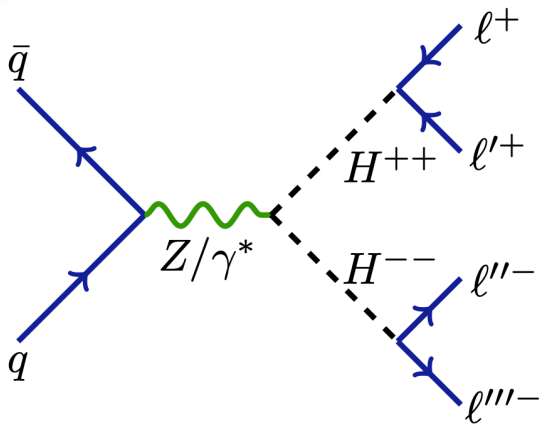
Obs.(exp.) limit on BR: 0.107 (0.077)



Eur. Phys. J. C 83 (2023) 933

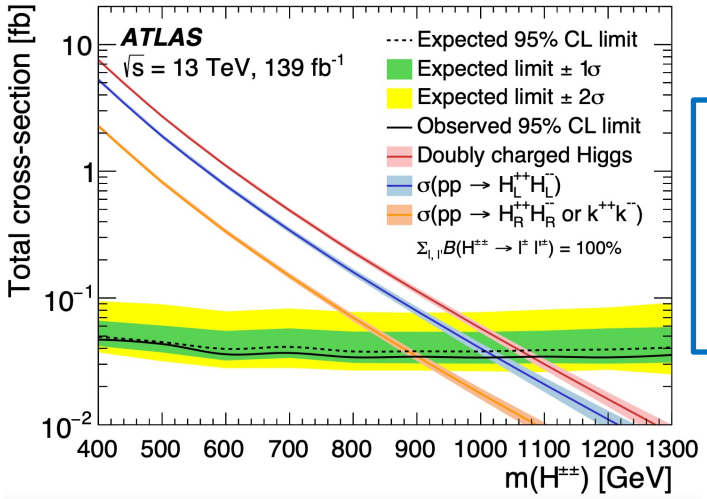
Obs.(exp.) limit on BR: 0.15 (0.08)

Search for Doubly Charged Higgs



Predicted by various BSM models such as LRSMs, type-II seesaw models, Zee–Babu neutrino mass model, etc

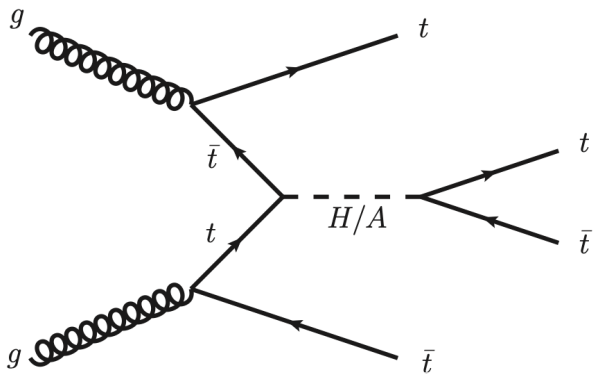
- ≥ 2 tight leptons (e/μ, leptonic τ decays)
- Lepton-flavor-violating decays allowed
- 3 SRs: $l^{\pm}l^{\pm}$, $l^{\pm}l^{\pm}l^{\mp}$, $l^{+}l^{+}l^{-}l^{-}$, $m(l^{\pm}, l^{\pm})_{lead}$ > 300 GeV



Mass below 1080 (900) GeV excluded for LRSMs (Zee-Babu model)

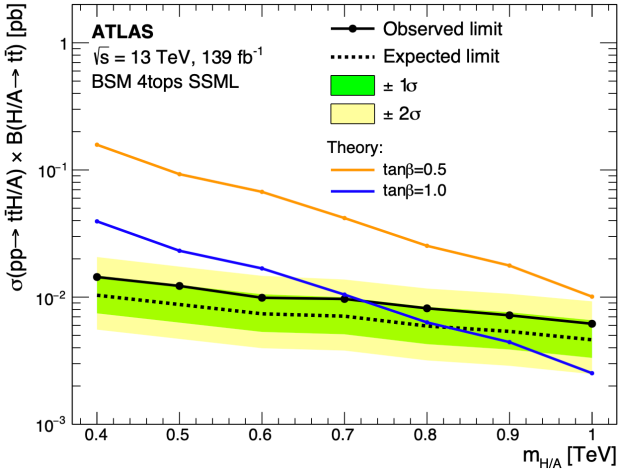
arXiv:2211.07505

Search for Heavy Higgs in 4 Top Events



Predicted by 2HDM, heavy Higgs mass assumed to be 400 – 1000 GeV

- Events selected with 2 same-sign leptons or ≥3 leptons; ≥6 jets (≥2 of which are b-jets)
- Major bkg. coming from SM 4-top, ttW/Z/H
- BDT trained to separate sig. and bkg., used for final fitting



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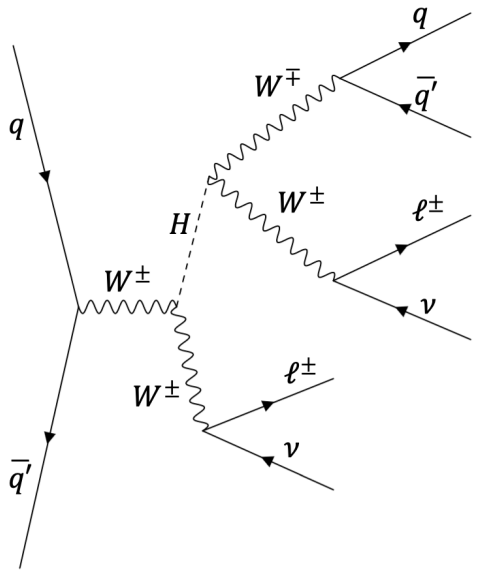
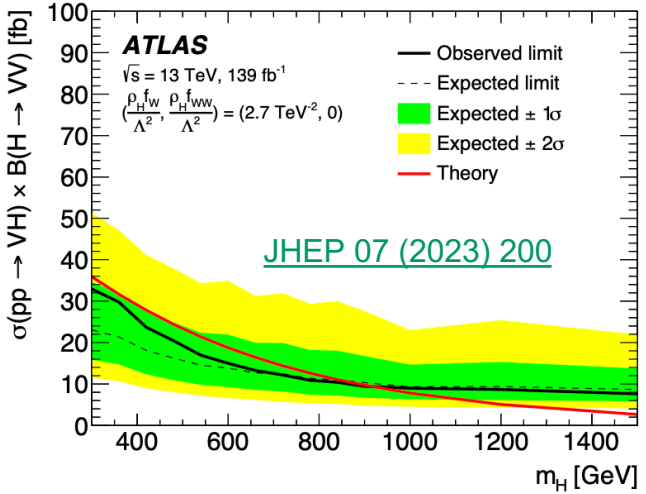
Search for Heavy Higgs via WH Mode

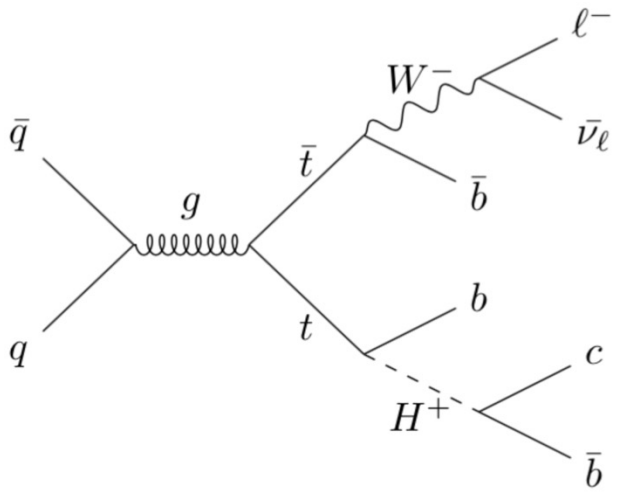


A generic search for heavy H→WW→lvqq in the model where H is fermiophobic

- Single lepton un-prescaled trigger used
- Selected two same-sign leptons plus MET together with 2 small-R jets (resolved SR) or 1 large-R jet (boosted SR)
- No deviation from SM seen

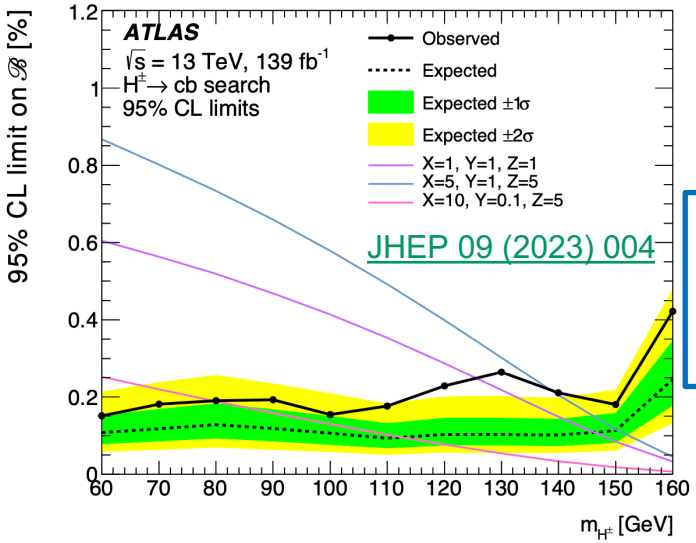


Search for Charged Higgs in Top Decays

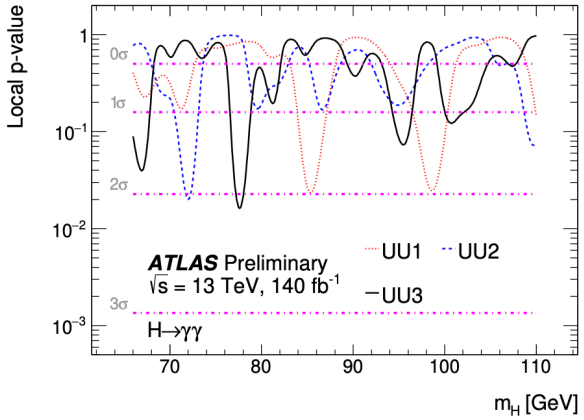


Predicted by 3HDM, where the lightest charged Higgs can be lighter than top quark

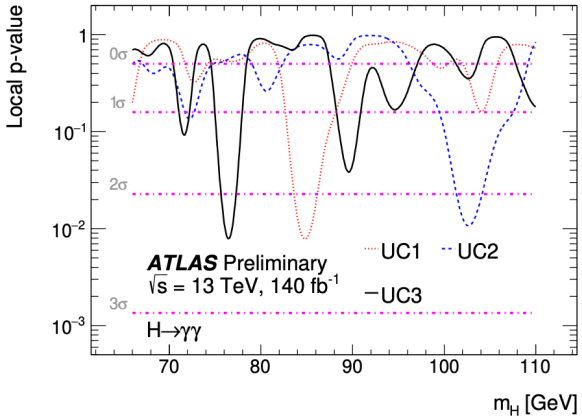
- Events selected with 1 e/μ and ≥4 jets
- NN trained to separate sig. vs bkg. (mainly from ttbar+jets) and used for fitting
- No significant data excess seen



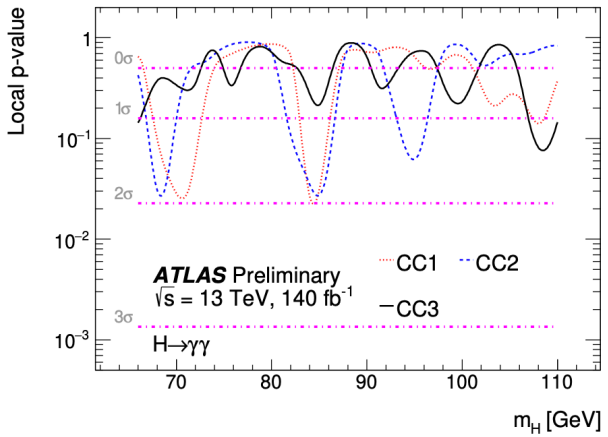
Local (global) significance for 130 GeV is 3.0 (2.5)σ



(a)

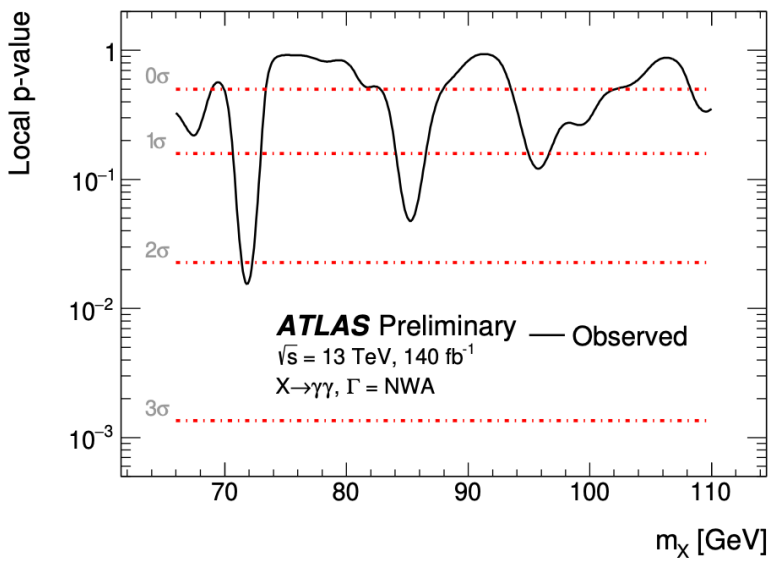


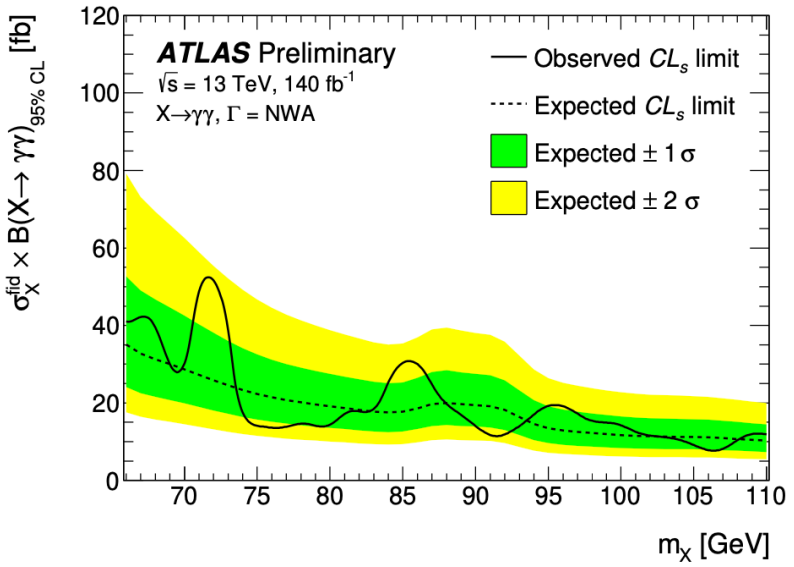
(b)



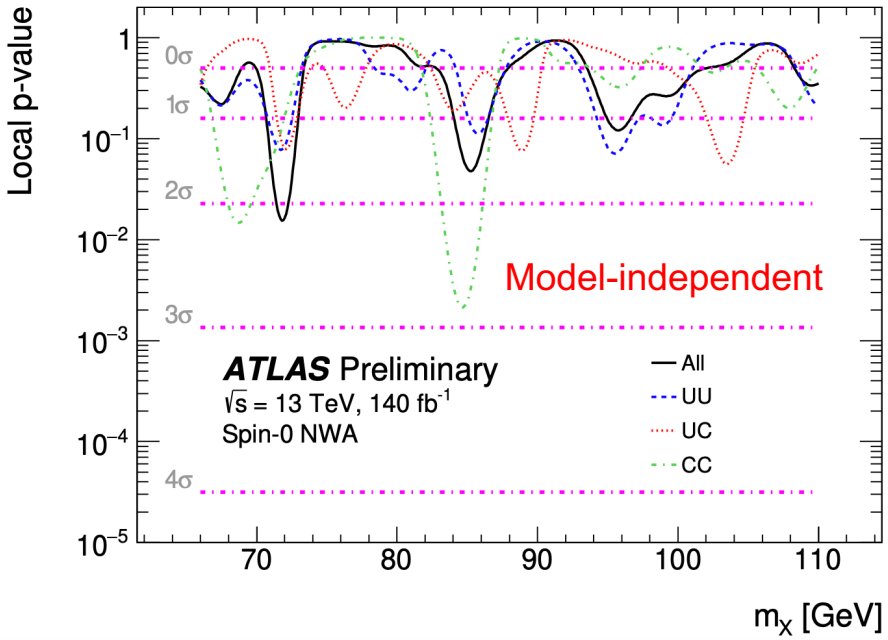
(c)

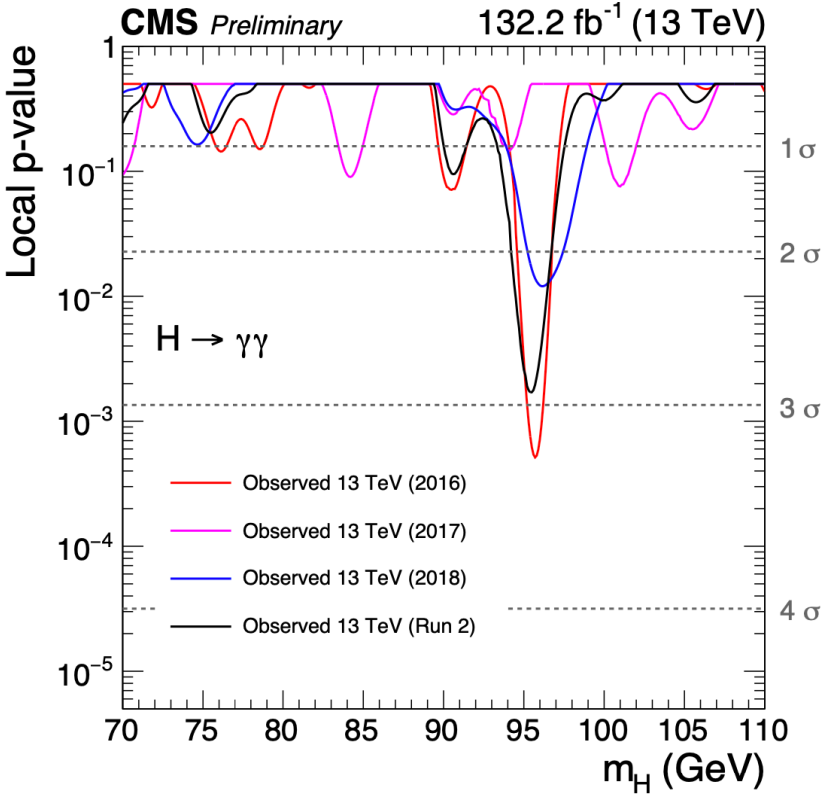
Model-dependent

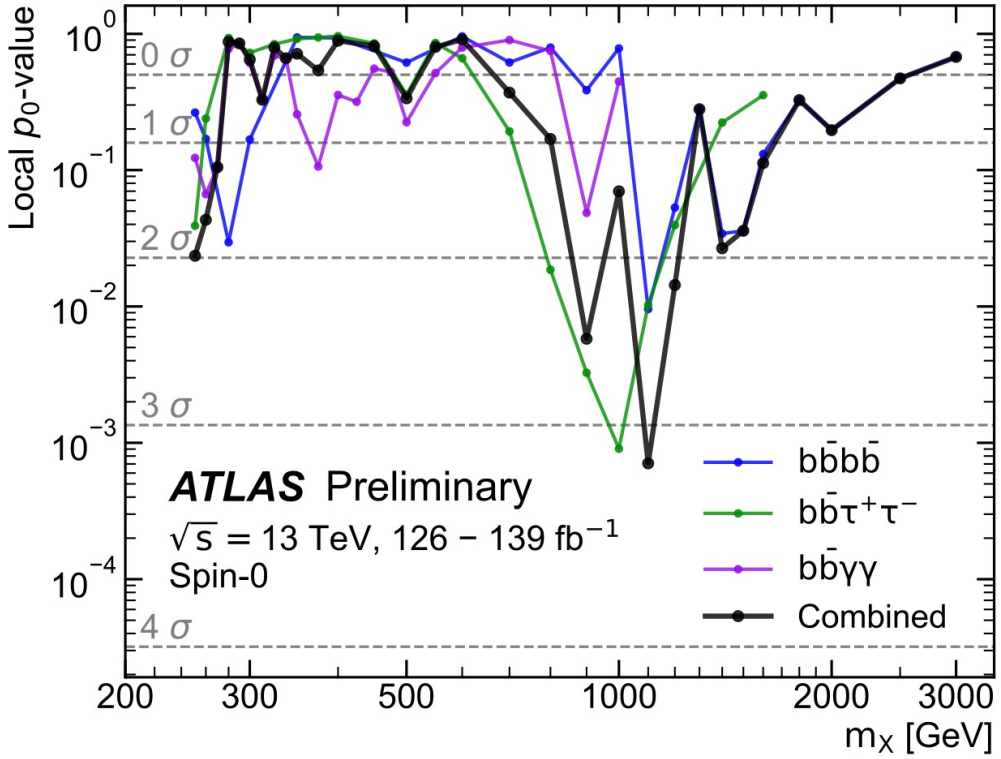




Model-independent


Local p-value
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0σ
1σ
2σ
3σ
4σ
Model-independent
ATLAS Preliminary
√s = 13 TeV, 140 fb-1
Spin-0 NWA
All
UU
UC
CC
70
80
90
100
110
m_X [GeV]


CMS Preliminary
132.2 fb-1 (13 TeV)
Local p-value
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
H → γγ
Observed 13 TeV (2016)
Observed 13 TeV (2017)
Observed 13 TeV (2018)
Observed 13 TeV (Run 2)
1 σ
2 σ
3 σ
4 σ
70
75
80
85
90
95
100
105
110
m_H (GeV)


Local p_0-value
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0 σ
1 σ
2 σ
3 σ
4 σ
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 126 − 139 fb^{-1}
Spin-0
$b\bar{b}b\bar{b}$
$b\bar{b}\tau^+\tau^-$
$b\bar{b}\gamma\gamma$
Combined
200
300
500
1000
2000
3000
m_X [GeV]