

Exotic and invisible Higgs decays at the LHC

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- Introduction
- Invisible Higgs decays
- $H \rightarrow \text{scalars}$
- $H \rightarrow Z_d$
- Lepton-flavor violating Higgs decays
- Summary

Introduction

Since the discovery of the Higgs in 2012, measurements agree very well with the Standard Model.

But still unanswered questions for which Higgs could play a major role, such as:

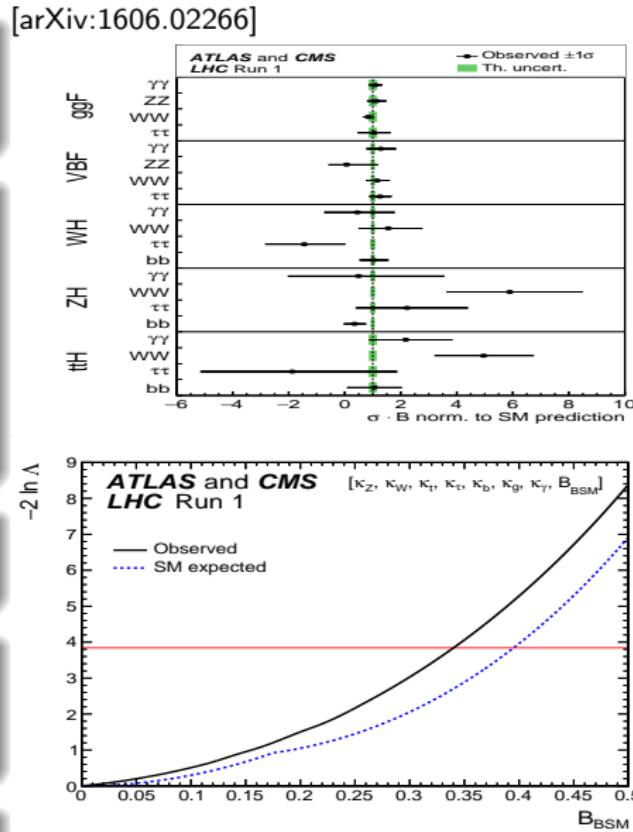
- Fine tuning?
 - Dark matter?
 - Matter/antimatter asymmetry?

Many BSM models predict nonstandard “exotic” decays of the 125 GeV Higgs.

Measurements of visible decays limit branching fraction to non-SM particles: $\mathcal{B}_{\text{BSM}} < 0.34$ (0.39).

Still plenty of room for beyond-SM physics in Higgs decays! ATLAS

ATLAS Run2: $\mathcal{B}_{\text{inv}} < 0.09$; $\mathcal{B}_{\text{undet}} < 0.19$ [ATLAS-CONF-2020-027]



Searches covered

Include only recent searches using the full 13 TeV Run 2 data set.

Not considering searches for long-lived particles.

Invisible Higgs decays

$(V \rightarrow \text{had})/\text{monojet} + (H \rightarrow \text{inv})$

$(Z \rightarrow \ell\ell) + (H \rightarrow \text{inv})$

VBF + $(H \rightarrow \text{inv})$

$t\bar{t}(H \rightarrow \text{inv})$

Higgs \rightarrow scalars

$H \rightarrow aa \rightarrow \gamma\gamma\gamma\gamma$

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

$ZH \rightarrow \ell\ell b\bar{b} + E_T^{\text{miss}}$

Dark sector Higgs decays

$H \rightarrow Z_d Z_d \rightarrow 4\ell$

$H \rightarrow ZZ_d \rightarrow 4\ell$

Also $H \rightarrow aa \rightarrow 4\ell$, $H \rightarrow Za \rightarrow 4\ell$

Lepton flavor violation + rare decays

$H \rightarrow e\tau/\mu\tau$

$H \rightarrow ee/e\mu$

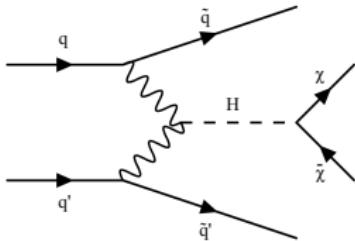
Invisible Higgs decays

A weakly-interacting, massive dark matter particle could interact with the SM Higgs boson.

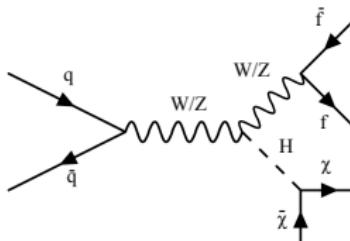
Many BSM theories predict Higgs decays to “stable” dark matter particles.

SM BR for $H \rightarrow \text{invisible}$ $\mathcal{B}_{\text{inv}}(4\nu)$ is $\sim 0.1\%$.

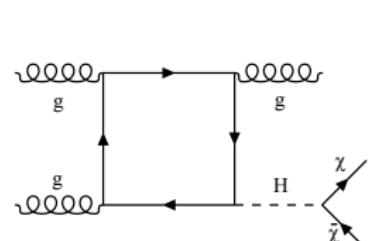
Look for VBF or W/Z or jet recoiling against invisibly-decaying Higgs.



VBF



W/Z



ggF

$H \rightarrow \text{invisible}: E_T^{\text{miss}} + (V \rightarrow J) \text{ or monojet}$



[arXiv:2107.13021]

Selection

$p_T^{\text{miss}} > 250 \text{ GeV}$

No ℓ , γ , b -tags.

Jet $> 100 \text{ GeV}$ and $|\eta| < 2.4$.

Mono- V (high- and low-purity):

Large- R jet $> 250 \text{ GeV}$ and $|\eta| < 2.4$

$65 < m_J < 105 \text{ GeV}$

Consistent with W/Z decay.

Separate mono-jet, and high-low purity mono- V categories.

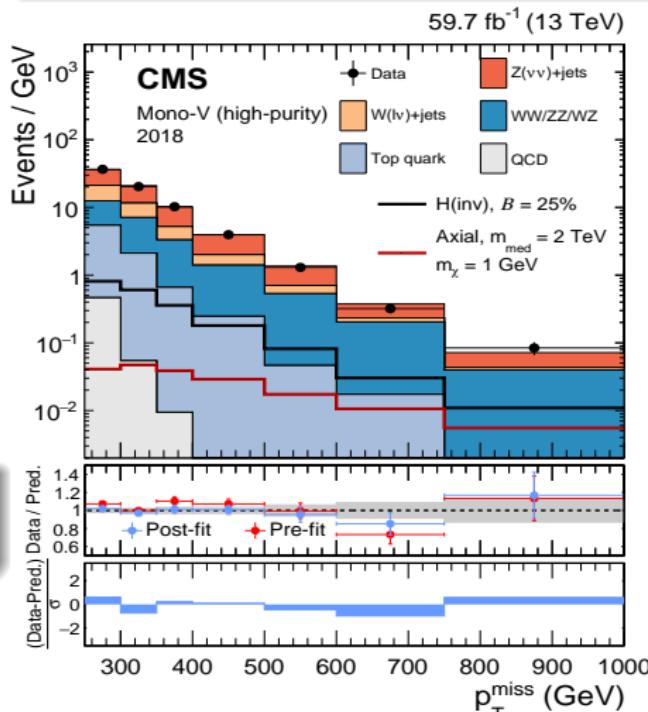
Combination over all channels and full Run-2 (137 fb^{-1}):

$\mathcal{B}_{\text{inv}} < 0.278$ at 95% CL
(exp: 0.253)

(All \mathcal{B}_{inv} results here assume the SM Higgs boson production cross section.)

Backgrounds

$V + \text{jets}$ estimated from CRs with leptons, photons.

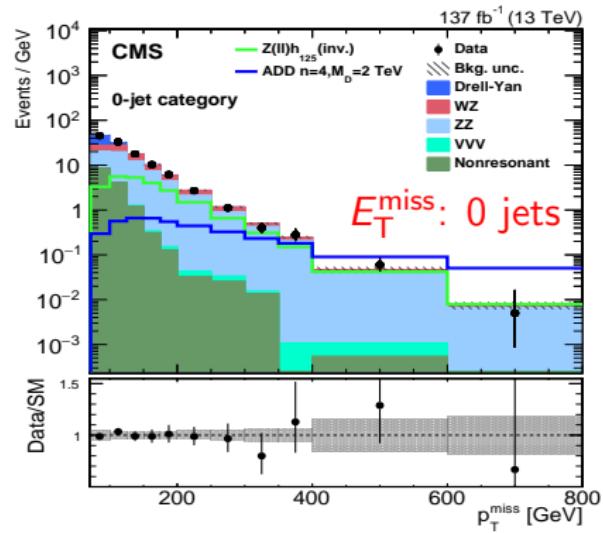
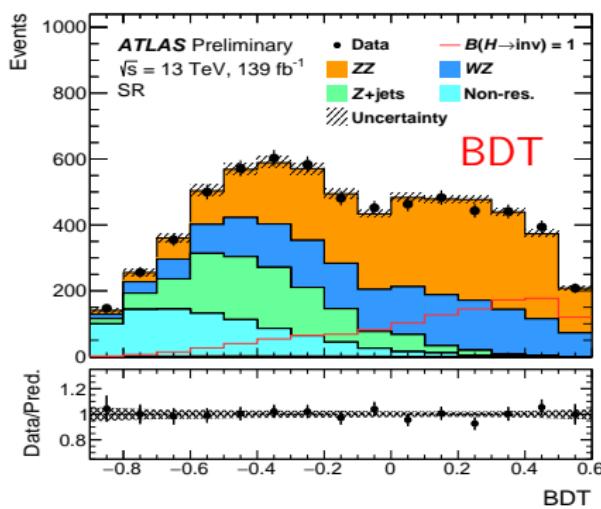


$H \rightarrow \text{invisible}: E_T^{\text{miss}} + (Z \rightarrow \ell\ell)$

Require $E_T^{\text{miss}} \sim \text{back-to-back}$ with $Z \rightarrow \ell\ell$.

BG mostly $(Z \rightarrow \ell\ell)(Z \rightarrow \nu\nu)$, $(Z \rightarrow \ell\ell)(W \rightarrow \ell\nu)$, and $Z + \text{jets}$.

ATLAS: Use BDT; CMS: Fit E_T^{miss} .



ATLAS: $\mathcal{B}_{\text{inv}} < 0.18 (0.18) [95\% \text{ CL}]$

CMS: $\mathcal{B}_{\text{inv}} < 0.29 (0.25) [95\% \text{ CL}]$

$H \rightarrow \text{invisible}: E_T^{\text{miss}} + \text{VBF}$

Selection

$E_T^{\text{miss}} > 200 \text{ GeV}; H_T^{\text{miss}} > 180 \text{ GeV}$

2 jets $|\eta| < 4.5$; $|\Delta\eta(jj)| > 3.8$; $\eta_1\eta_2 < 0$

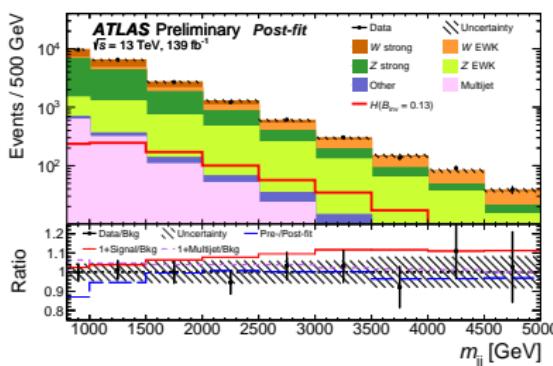
$p_T(j1) > 80 \text{ GeV}; p_T(j2) > 50 \text{ GeV}$

$\Delta\phi(jj) < 2.0$; $m_{jj} > 0.8 \text{ TeV}$

No leptons or photons

Additional jets consistent with QCD radiation

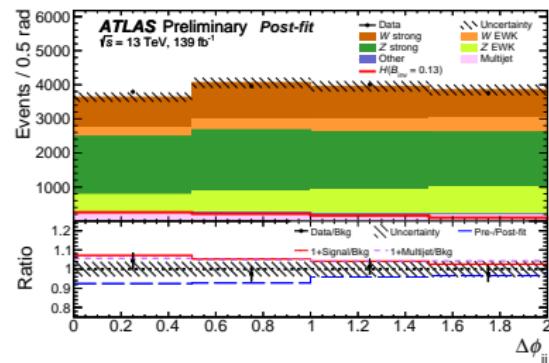
11 bins in m_{jj} , $\Delta\phi(jj)$, and N_{jets} . Simultaneous fit to SR and CRs.



Backgrounds

Mostly $(Z \rightarrow \nu\nu) + \text{jets}$,
 $(W \rightarrow \ell\nu) + \text{jets}$.

Constrain BG using CRs with 1 or 2 leptons.



$\mathcal{B}_{\text{inv}} < 0.13$ at 95% CL (exp: $0.13^{+0.05}_{-0.04}$)

CMS: $\mathcal{B}_{\text{inv}} < 0.17$ (0.11) [CMS-PAS-HIG-20-003]

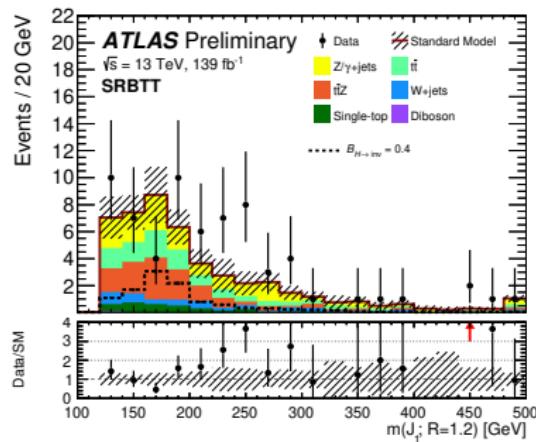
$H \rightarrow \text{invisible}: E_T^{\text{miss}} + t\bar{t}$

All-hadronic $t\bar{t}$ with 2 b -tagged jets

$E_T^{\text{miss}} > 250 \text{ GeV}$

t candidates identified by reclustering decay products into $R = 1.2$ jet.

Leading reclustered jet mass:



$\mathcal{B}_{\text{inv}} < 0.94 \text{ (0.64)} \text{ at 95\% CL}$

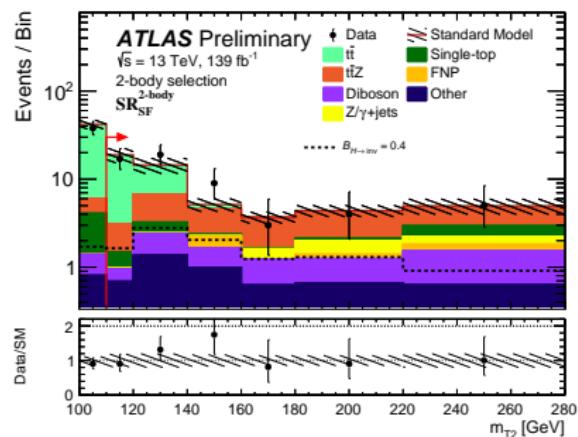
2 OS leptons, jets, E_T^{miss}

1 b -tagged jet

E_T^{miss} significance > 12

stransverse mass m_{T2} :

$$\min_{q_{T,1}+q_{T,2}=p_T^{\text{miss}}} \{ \max[m_T(p_{T,\ell 1}, q_{T,1}), m_T(p_{T,\ell 2}, q_{T,2})] \}$$

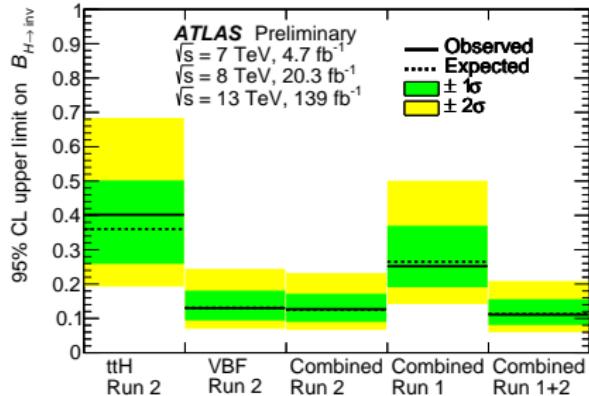


$\mathcal{B}_{\text{inv}} < 0.37 \text{ (0.42)} \text{ at 95\% CL}$

CMS 36 fb^{-1} result: $\mathcal{B}_{\text{inv}} < 0.46 \text{ (0.48)}$ (backup)

$H \rightarrow$ invisible: Combination

Combination includes Run 2 VBF and $t\bar{t}H$ results, but not ZH .

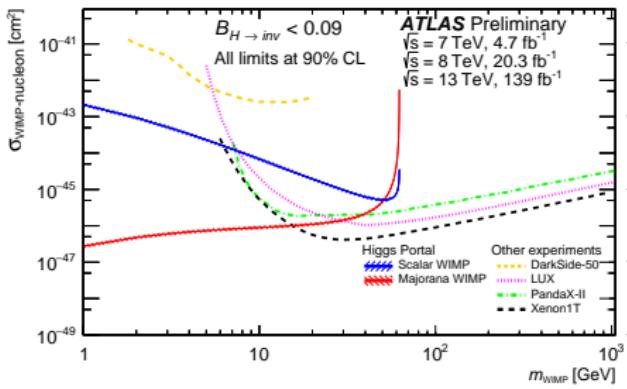


95% CL; obs (exp)

Run 1	$\mathcal{B}_{\text{inv}} < 0.25$ (0.27)
Run 2 VBF	$\mathcal{B}_{\text{inv}} < 0.13$ (0.13)
Run 2 $t\bar{t}H$	$\mathcal{B}_{\text{inv}} < 0.40$ (0.36)
Run 2	$\mathcal{B}_{\text{inv}} < 0.13$ (0.12)
All	$\mathcal{B}_{\text{inv}} < 0.11$ (0.11)

Higgs portal: interpret in terms of WIMP mass and nuclear scattering cross section.

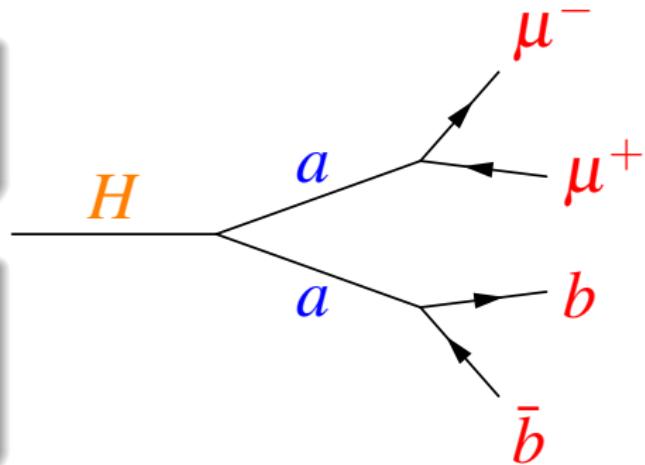
90% CL: $\mathcal{B}_{\text{inv}} < 0.09$ (0.09)



Higgs \rightarrow scalars

Some extensions to the SM include Higgs decays via a pair of on-shell (pseudo)scalars, eg, 2HDM+S.

$a \rightarrow bb$ generally dominates, but other decays may also be significant depending on the model, such as $a \rightarrow \mu\mu, a \rightarrow \tau\tau, a \rightarrow \gamma\gamma, a \rightarrow gg$.

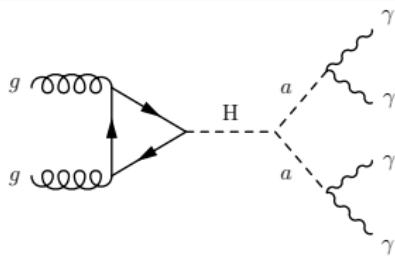


Upper limit of sensitivity $m_a < 62.5$ GeV set by requirement of $H \rightarrow aa$. Most searches sensitive down to 15–20 GeV — below that, decay products can start to merge.

$H \rightarrow aa \rightarrow \gamma\gamma\gamma\gamma$

Decay to 4 resolved γ has low SM background.

In some models, a may have only decays to photons



Use BDT to separate S/B.

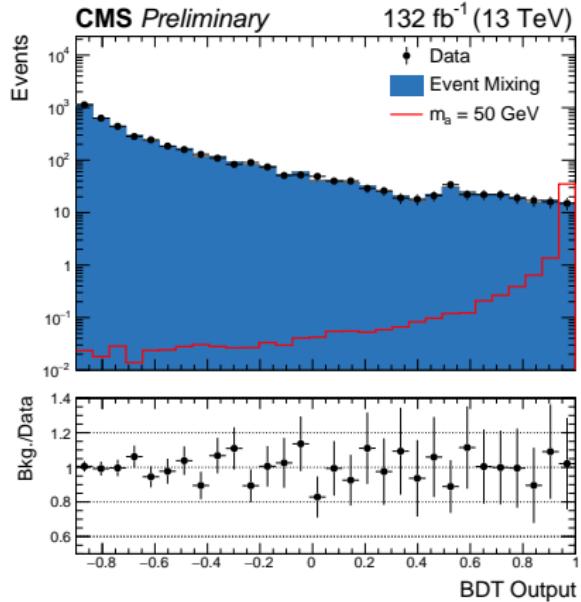
Hypothesized m_a is one input to BDT.

[arXiv:1601.07913]

BDT variables chosen to be uncorrelated with $m_{\gamma\gamma\gamma\gamma}$.

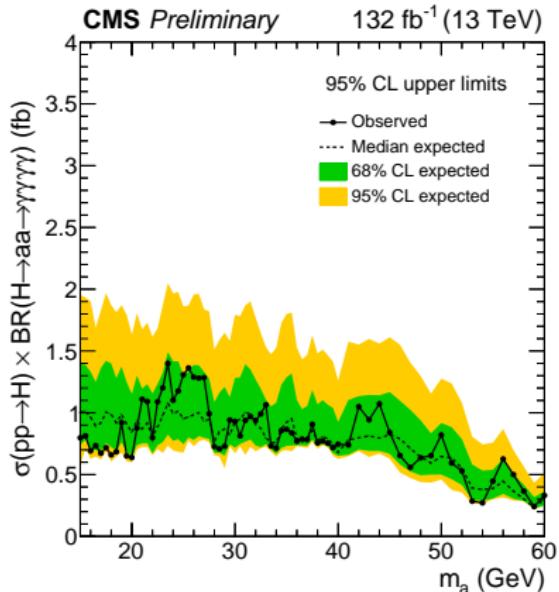
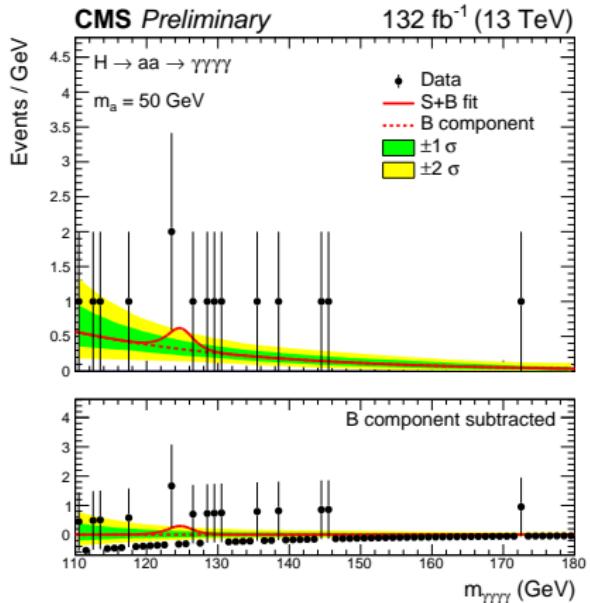
Event mixing used for background training sample.

Use $m_{\gamma\gamma\gamma\gamma}$ as final discriminant. Fit to sum of signal+background models.



$H \rightarrow aa \rightarrow \gamma\gamma\gamma\gamma$ 

[CMS-PAS-HIG-21-003]



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

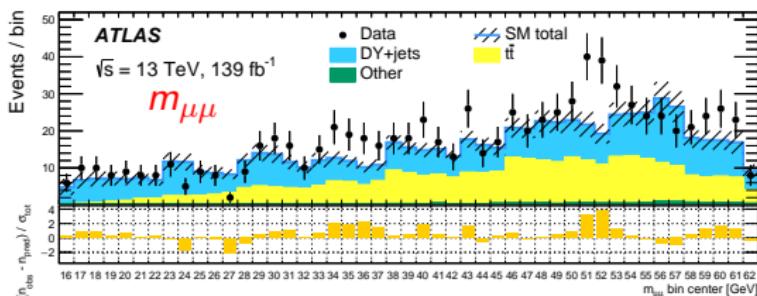
$a \rightarrow bb$ expected to dominate, but $a \rightarrow \mu\mu$ can be significant in 2HDM models with enhanced lepton couplings.

$\mu^+\mu^-$ with $15 < m_{\mu\mu} < 65$ GeV.

Exactly 2 b -tags.

Kinematic fit of bb to enforce $m_{bb} \approx m_{\mu\mu}$ to improve $m_{bb\mu\mu}$ resolution.

$110 < m_{bb\mu\mu}^{\text{fit}} < 140$ GeV; $E_T^{\text{miss}} < 60$ GeV



BR upper limits: 0.2×10^{-4} to 4.0×10^{-4} .

Significance of excess: 3.3σ (local) / 1.7σ (global).

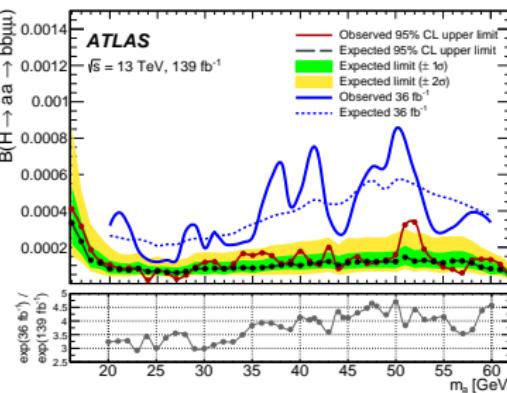
Background mostly $Z + \text{jets}$ and $t\bar{t}$.

Use BDT to improve S/B discrimination.

Top CR: $E_T^{\text{miss}} > 60$ GeV

DY CR: $m_{bb\mu\mu}$ inconsistent with $H(125)$.

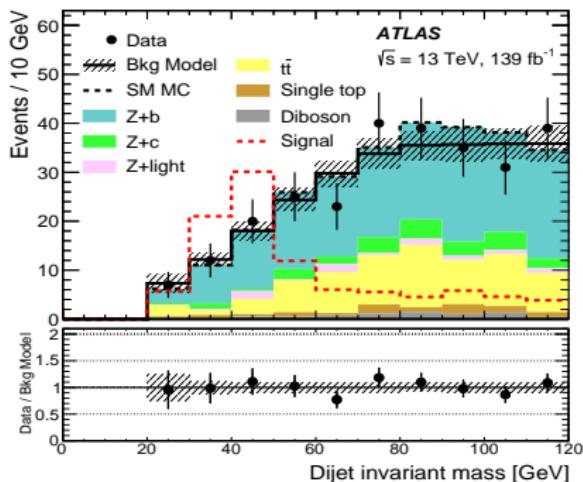
Fit signal + control regions and search for excess in $m_{\mu\mu}$.



Search for cascade decay $H \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^0 \rightarrow (a \rightarrow b\bar{b}) \tilde{\chi}_1^0 \tilde{\chi}_1^0$

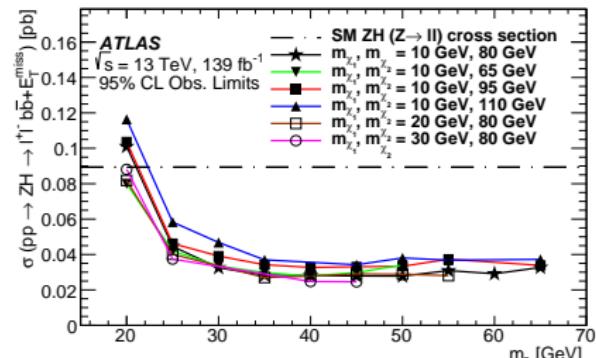
Selection

$81 < m(\ell\ell) < 101$ GeV; $p_T(\ell\ell) > 40$ GeV
 ≥ 2 jets; ≥ 1 b -tag; $20 < m(jj) < 120$ GeV
 $E_T^{\text{miss}} > 100$ GeV;
 $0.8 < (p_T(jj) + E_T^{\text{miss}})/p_T(\ell\ell) < 1.2$



Background primarily $Z + \text{H.F.}$ and $t\bar{t}$.

Fit $m(jj)$ in signal and control regions.

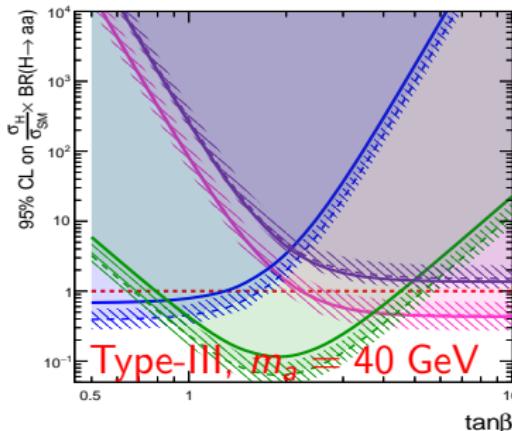
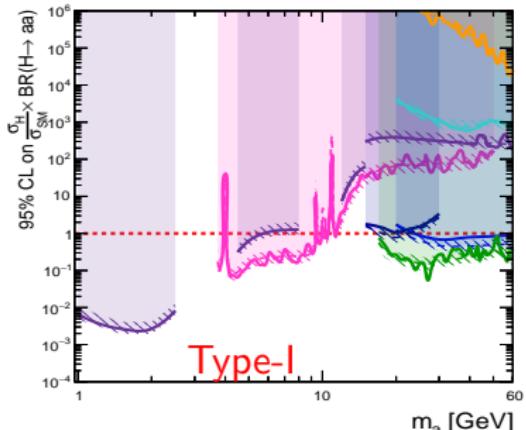


Assuming $\mathcal{B}(\tilde{\chi}_2^0 \rightarrow a\tilde{\chi}_1^0) = \mathcal{B}(a \rightarrow b\bar{b}) = 100\%$ and $m_{\tilde{\chi}_1^0, \tilde{\chi}_2^0} = 10, 80$ GeV:

$\mathcal{B}(H \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^0) < 31\% \text{ (95\% CL)}$
for $35 < m_a < 55$ GeV.

Interpret as limits on
 $H \rightarrow aa$ branching ratio
in the context of specific
2HDM+S models.

Includes results current
through 03/2021.



ATLAS Preliminary

March 2021

Run 1: $\sqrt{s} = 8$ TeV

Run 2: $\sqrt{s} = 13$ TeV

2HDM+S Type-I

expected $\pm 1\sigma$
observed

Run 1 20.3 fb ⁻¹	$H \rightarrow aa \rightarrow \mu\mu\tau\tau$	PRD 92 (2015) 052002
Run 1 20.3 fb ⁻¹	$H \rightarrow aa \rightarrow \gamma\gamma\gamma\gamma$	EPJC 76 (2016) 210
Run 2 1.1 fb ⁻¹	$H \rightarrow aa \rightarrow \mu\mu\mu\mu$	JHEP 06 (2018) 166
Run 2 36.1 fb ⁻¹	$H \rightarrow aa \rightarrow b\bar{b}b\bar{b}$	JHEP 10 (2018) 031
Run 2 36.1 fb ⁻¹	$H \rightarrow aa \rightarrow b\bar{b}b\bar{b}$	PRD 102 (2020) 112006
Run 2 36.7 fb ⁻¹	$H \rightarrow aa \rightarrow \gamma\gamma\eta\eta$	PLB 782 (2018) 750
Run 2 139 fb ⁻¹	$H \rightarrow aa \rightarrow b\bar{b}\mu\mu$	ATLAS-CONF-2021-009

ATLAS Preliminary

March 2021

Run 1: $\sqrt{s} = 8$ TeV

Run 2: $\sqrt{s} = 13$ TeV

2HDM+S Type-III, $m_a = 40$ GeV

expected $\pm 1\sigma$
observed

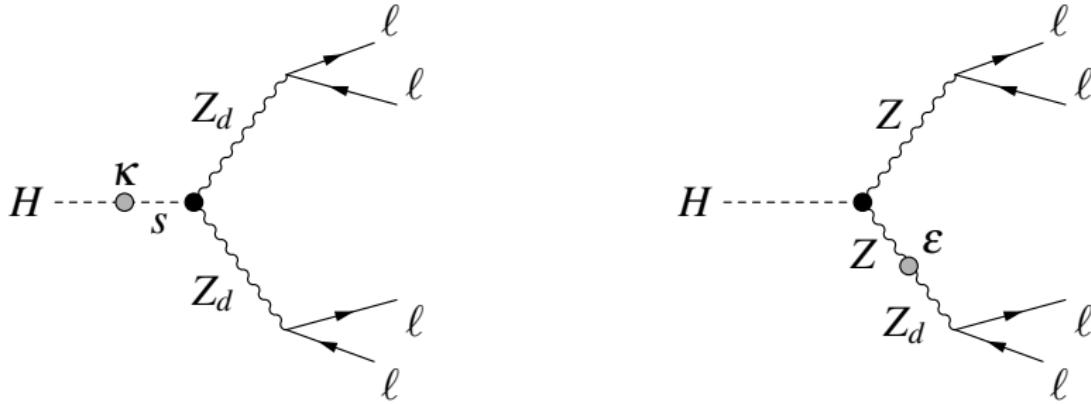
Run 1 20.3 fb ⁻¹	$H \rightarrow aa \rightarrow \mu\mu\tau\tau$	PRD 92 (2015) 052002
Run 2 36.1 fb ⁻¹	$H \rightarrow aa \rightarrow b\bar{b}b\bar{b}$	JHEP 10 (2018) 031
Run 2 139 fb ⁻¹	$H \rightarrow aa \rightarrow b\bar{b}\mu\mu$	ATLAS-CONF-2021-009
Run 2 36.1 fb ⁻¹	$H \rightarrow aa \rightarrow \mu\mu\mu\mu$	JHEP 06 (2018) 166

Higgs decays to dark photons

Many SM extensions include a $U(1)$ dark gauge symmetry with gauge boson Z_d mixing with SM Higgs via κ and with hypercharge gauge boson via ϵ .

Gives rise to $H \rightarrow Z_d Z_d$ and $H \rightarrow ZZ_d$.

Z_d has significant decays to $\ell\ell$ ($\sim 0.2\text{--}0.3$). Prompt for $\epsilon \gtrsim 10^{-5}$.



Also sensitive to $H \rightarrow aa \rightarrow 4\mu$ if $\mathcal{B}(a \rightarrow \mu\mu)$ is significant.

Could be $\sim 10\%$ for Type-II 2HDM+S with $\tan\beta \sim 5$ and $m_a < 4$ GeV.

$H \rightarrow Z_d Z_d / aa \rightarrow 4\ell$

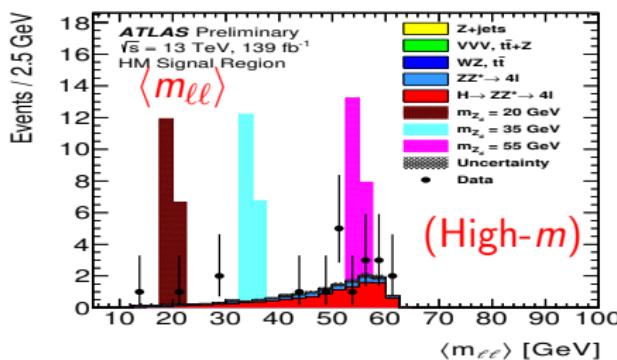
Two ℓ pairs: $(ee)(ee)$, $(ee)(\mu\mu)$, $(\mu\mu)(\mu\mu)$.

$m_{4\ell}$ consistent with m_H .

$m_{\ell\ell}$ inconsistent with $J/\psi/\Upsilon$ and mispaired Z .

Mass compatibility of pairs: $m_{12}/m_{34} \gtrsim 0.85$.

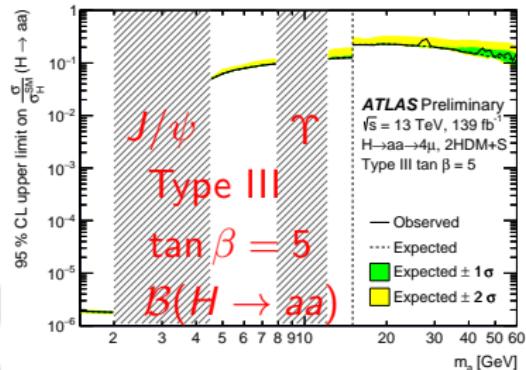
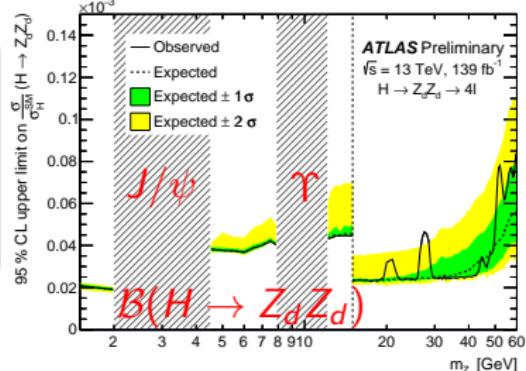
Consider only 4μ for $1 < m_X < 15$ GeV.



Main bkg: $H \rightarrow ZZ^*$ and ZZ^* .

High mass: 20 evts obs.; bkg: 15.6 ± 1.2

Low mass: 0 evts obs.; bkg: 0.9 ± 0.1



Also limits on model-independent fiducial cross sections and on κ' (in backup).

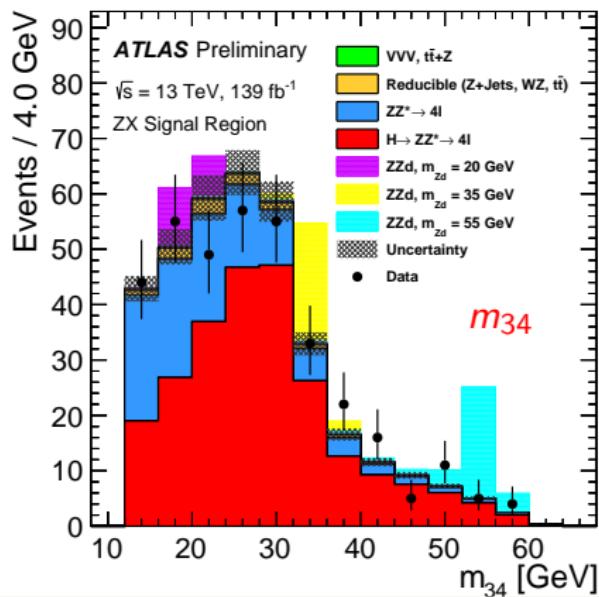
$H \rightarrow ZZ_d \rightarrow 4\ell$

Two ℓ pairs: (ee)(ee), (ee)($\mu\mu$), ($\mu\mu$)($\mu\mu$).

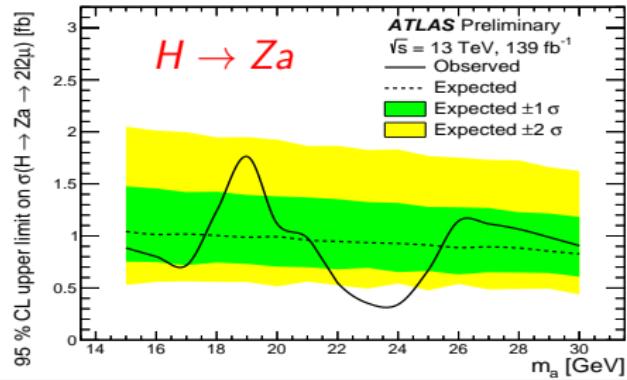
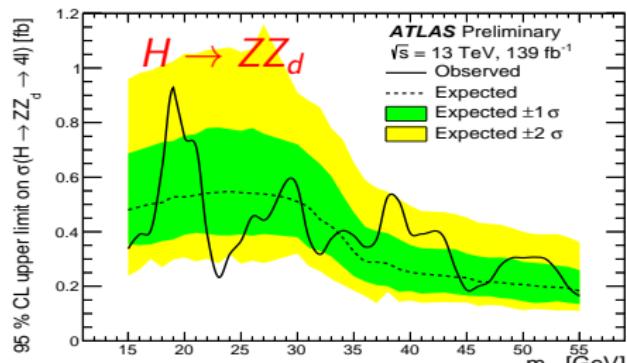
$m_{4\ell}$ consistent with m_H .

One pair (m_{12}) consistent with m_Z .

Look for peak in distribution of m_{34} .

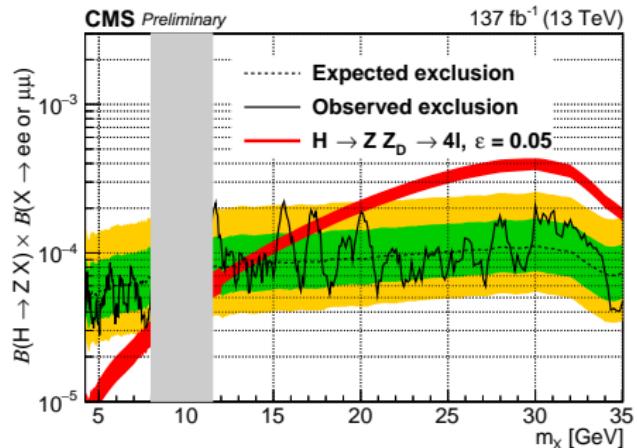
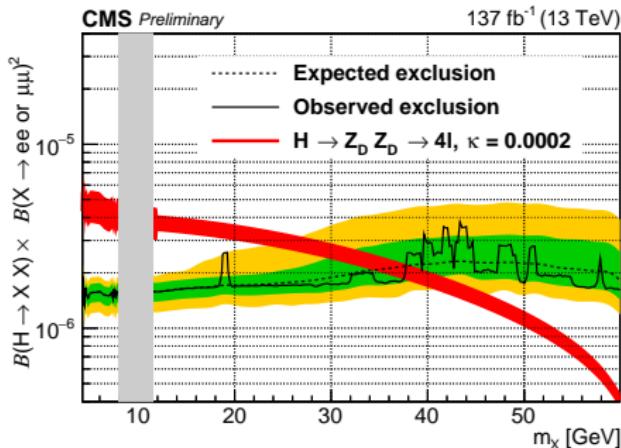


356 events observed; bkg: 319.7 ± 17.0



Also model-independent fiducial cross section limits and ϵ/δ limits (in backup).

Exclusion limits for comparable CMS analysis are similar.



Also limits on axion-like particle interpretation and on κ (in backup).

Lepton flavor violation and rare decays

$H \rightarrow \ell\ell'$ forbidden in SM but allowed in some extensions:
SUSY, composite Higgs, Randall-Sundrum, etc.

$H \rightarrow e\mu$ strongly constrained by $\mu \rightarrow e\gamma$ limits: $\mathcal{B}(H \rightarrow e\mu) < \mathcal{O}(10^{-8})$.
[arXiv:1209.1397]

However this assumes SM values of the Yukawa couplings Y_{ee} and $Y_{\mu\mu}$.
A direct search allows constraining $Y_{e\mu}$ without such assumptions.

Limits on rare τ decay $\tau \rightarrow \mu$ and $\tau \rightarrow e$ imply
 $\mathcal{B}(H \rightarrow \mu\tau)$ and $\mathcal{B}(H \rightarrow e\tau) < 10\%$. [arXiv:1309.3564]

Also interesting to look for anomalous $H \rightarrow ee$.
SM $\mathcal{B}(H \rightarrow ee) \approx 5 \times 10^{-9}$, far below the LHC sensitivity.

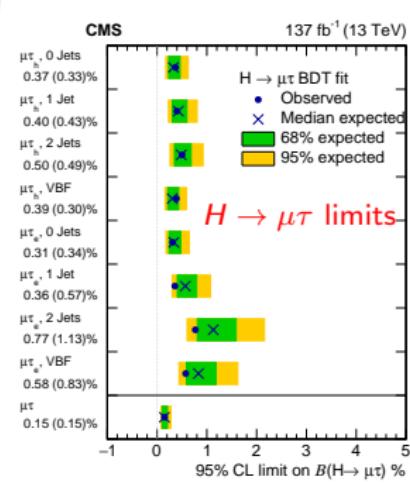
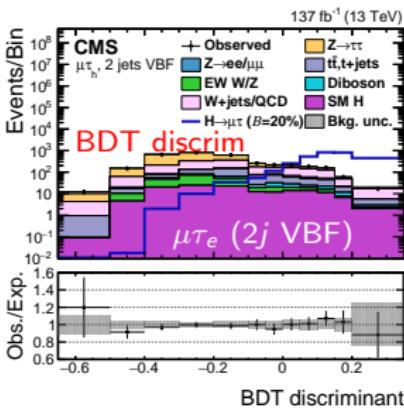
$H \rightarrow e\tau/\mu\tau$

Channels: $e\tau_h$, $e\tau_\mu$, $\mu\tau_h$, $\mu\tau_e$

Jet categories: 0j, 1j, 2j (ggH), VBF

Use BDTs to discriminate signal.

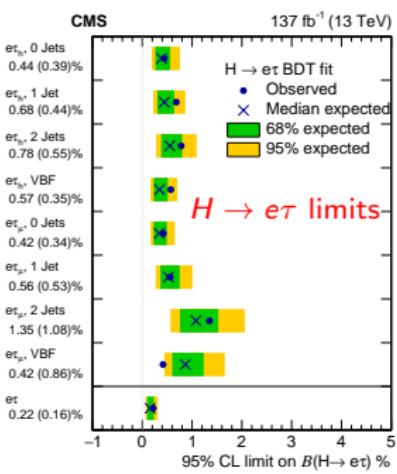
Joint fit to BDT output.



$$\mathcal{B}(H \rightarrow \mu\tau) < 0.15 \text{ (0.15)\%} \quad [95\% \text{ CL}]_{\text{obs (exp)}}$$

$$\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 1.11 \times 10^{-3}$$

Backgrounds: $Z \rightarrow \tau\tau$; $W + \text{jets}$ and QCD with jets misidentified as leptons.



$$\mathcal{B}(H \rightarrow e\tau) < 0.22 \text{ (0.16)\%} \quad [95\% \text{ CL}]_{\text{obs (exp)}}$$

$$\sqrt{|Y_{e\tau}|^2 + |Y_{\tau e}|^2} < 1.35 \times 10^{-3}$$

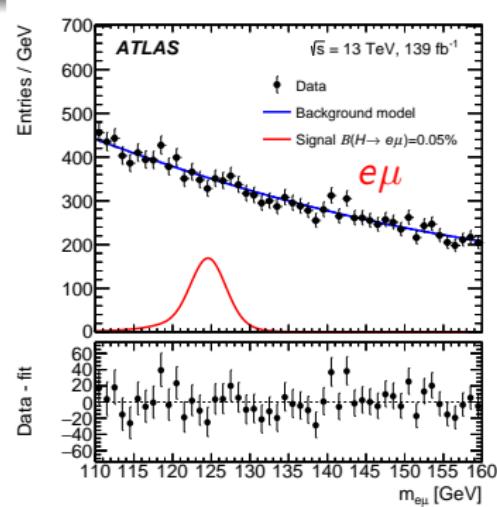
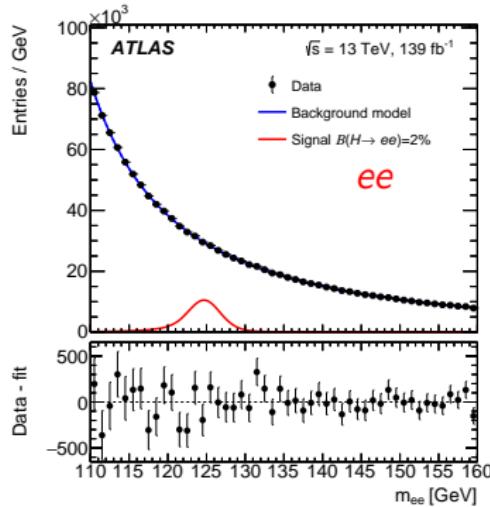
$H \rightarrow ee/e\mu$

Search for a peak around 125 GeV in ee and $e\mu$ distributions.

Divide into categories depending on kinematics of the leptons and any jets.

Fit to sum of signal and an analytic background model.

ee bkg dominated by $Z/\gamma^* \rightarrow ee$. $e\mu$ bkg includes $Z/\gamma^* \rightarrow \tau\tau$, $t\bar{t}$, WW , etc.



$$\mathcal{B}(H \rightarrow ee) < 3.6 \times 10^{-4} \quad (3.5 \times 10^{-4})$$

[95%] obs (exp)

$$\mathcal{B}(H \rightarrow e\mu) < 6.2 \times 10^{-5} \quad (5.9 \times 10^{-5})$$

Summary

Both experiments searching for nonstandard decays of the 125 GeV Higgs.

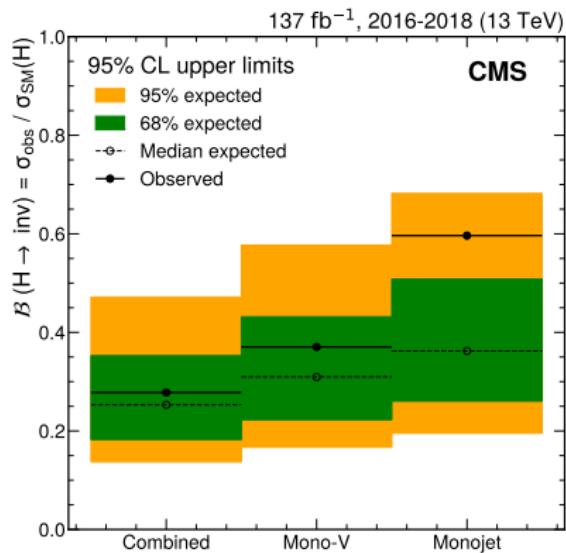
Converging on final results from Run 2.

Limits on $H \rightarrow$ invisible, $H \rightarrow aa$, $H \rightarrow ZZ_d/Z_dZ_d$, and
 $H \rightarrow e\tau/\mu\tau/e\mu/ee$.

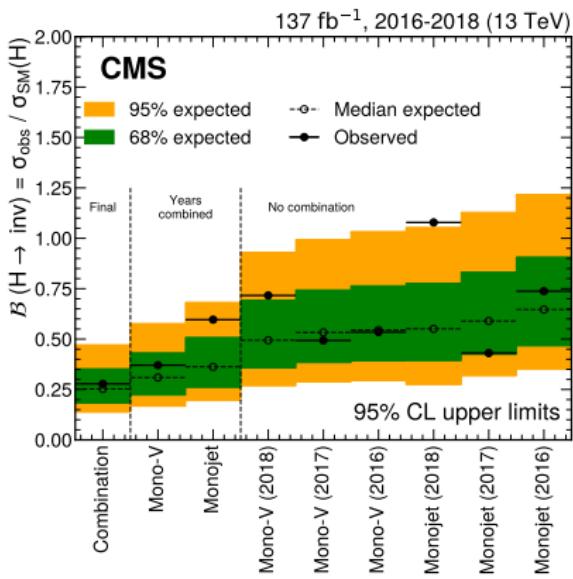
Many searches are statistically limited. Looking forward to improvements in LHC Run 3!

Backup

Result by channel:

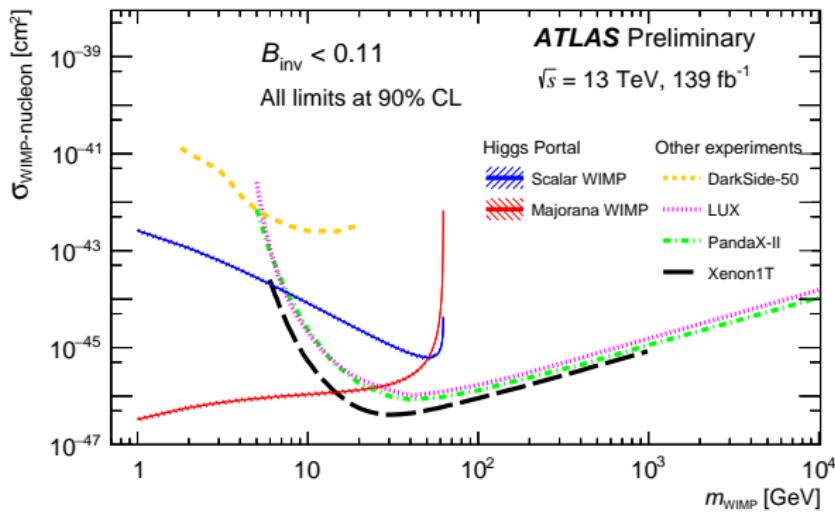


Result by channel and run period:



Higgs portal

Interpret in terms of WIMP mass and nuclear scattering cross section.



Selection

$p_T^{\text{miss}} > 250 \text{ GeV}$

2 jets $|\Delta\eta(jj)| > 1$

$p_T(j1) > 80 \text{ GeV}; p_T(j2) > 40 \text{ GeV}$

$m_{jj} > 200 \text{ GeV}; \Delta\phi(jj) < 1.5$

$\eta_1\eta_2 < 0$

No leptons or b -tags.

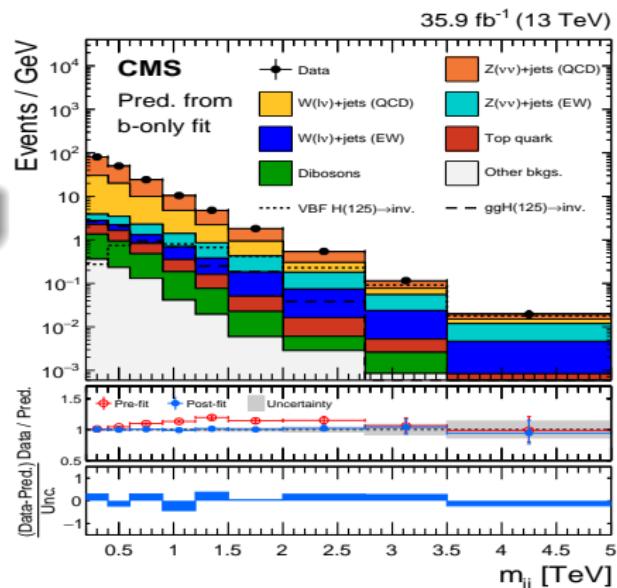
Fit shape of entire m_{jj} distribution.

$\mathcal{B}_{\text{inv}} < 0.33$ at 95% CL (exp: 0.25)

Backgrounds

Mostly $(Z \rightarrow \nu\nu) + \text{jets}$,
 $(W \rightarrow \ell\nu) + \text{jets}$.

Constrain BG using CRs with 1 or 2 leptons.



Selection

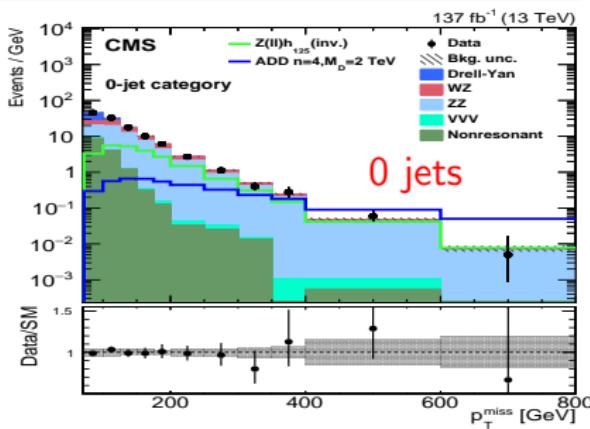
$p_T^{\text{miss}} > 100 \text{ GeV}$

$Z \rightarrow \ell\ell$ candidate ($|m_{\ell\ell} - M_Z| < 15 \text{ GeV}$)

$p_T(\ell\ell) > 60 \text{ GeV}; \Delta R(\ell\ell) < 1.8$

p_T^{miss} is back-to-back with $\ell\ell$, not dominated by soft terms, and away from any jet.

No b -tags or additional leptons; no more than 1 jet.



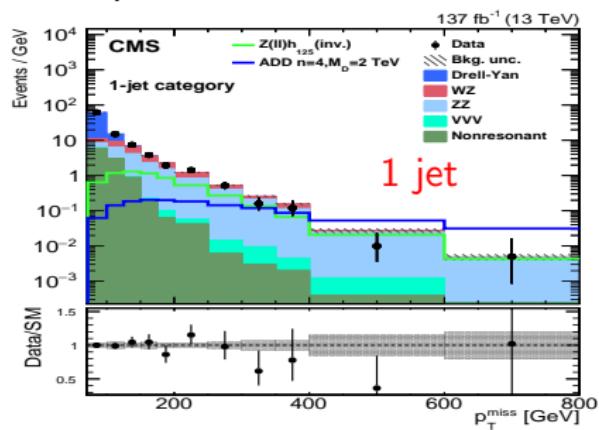
Backgrounds

$(Z \rightarrow \ell\ell)(Z \rightarrow \nu\nu)$ and

$(Z \rightarrow \ell\ell)(W \rightarrow \ell\nu)$ constrained from data in 3ℓ , 4ℓ CRs.

$e\mu$ CR constrains $t\bar{t}$, etc. Low- E_T^{miss} CR constrains DY.

Fit to E_T^{miss} distribution.



$$\mathcal{B}_{\text{inv}} < 0.29 \text{ at } 95\% \text{ CL (exp: } 0.25^{+0.09}_{-0.07})$$

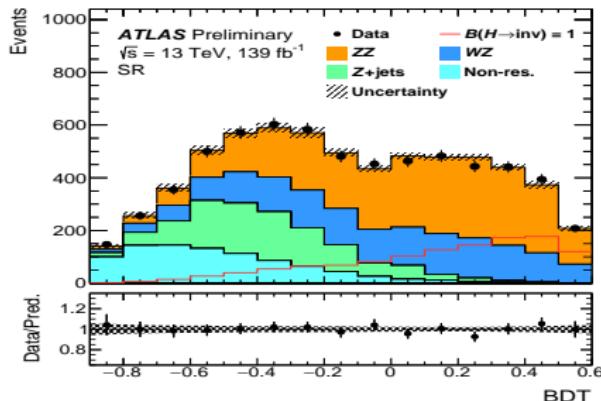
Selection

$E_T^{\text{miss}} > 90 \text{ GeV}$; $S_{E_T^{\text{miss}}} > 9$

$Z \rightarrow \ell\ell$ candidate ($76 < m_{\ell\ell} < 106 \text{ GeV}$)

$\Delta R(\ell\ell) < 1.8$

No b -tags or additional leptons



Backgrounds

$(Z \rightarrow \ell\ell)(Z \rightarrow \nu\nu)$ constrained with simulation and 4ℓ CR.

$(Z \rightarrow \ell\ell)(W \rightarrow \ell\nu)$ constrained with 3ℓ CR.

$Z + \text{jets}$ estimated from simulation.

$e\mu$ CR for $t\bar{t}$, $Z \rightarrow \tau\tau$, etc.

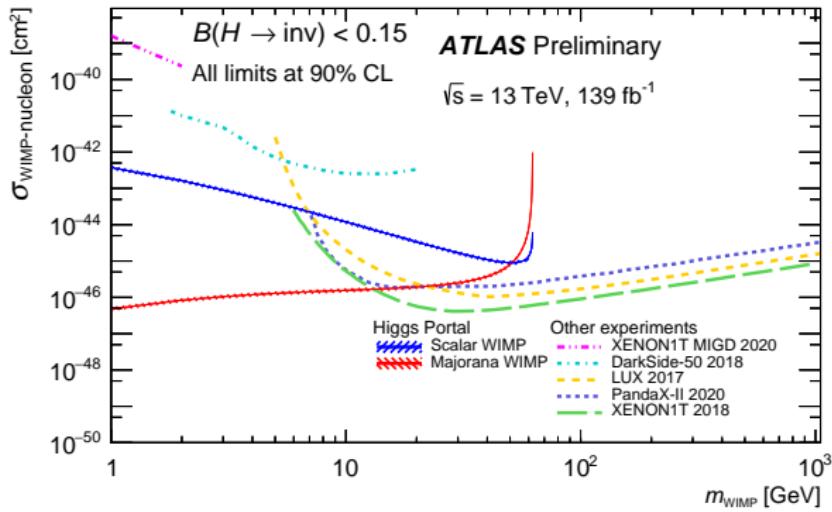
Sensitivity improved with BDT.

Simultaneous fit of BDT distribution in SR and CRs.

$$\mathcal{B}_{\text{inv}} < 0.18 \text{ at } 95\% \text{ CL (exp: 0.18)}$$

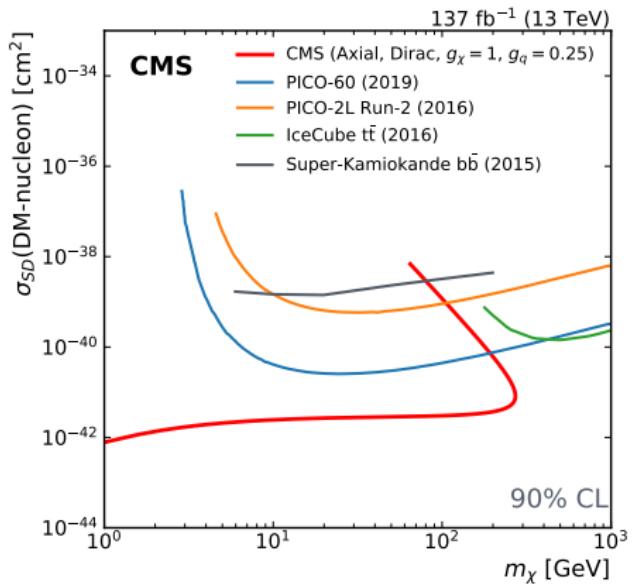
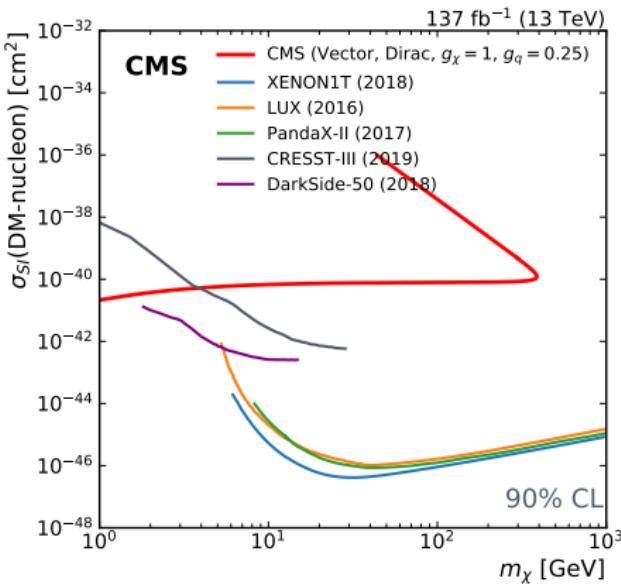
Higgs portal

Interpret in terms of WIMP mass and nuclear scattering cross section.



Higgs portal

Interpret in terms of WIMP mass and nuclear scattering cross section.



Selection

Resolved:

2 jets $65 < m_{jj} < 105$ GeV; $E_T^{\text{miss}} > 150$ GeV

Merged: Large- R jet consistent with W/Z decay; $E_T^{\text{miss}} > 250$ GeV

No extra ℓ ; no b -tags unassociated with signal jets.

Multijet suppression requirements.

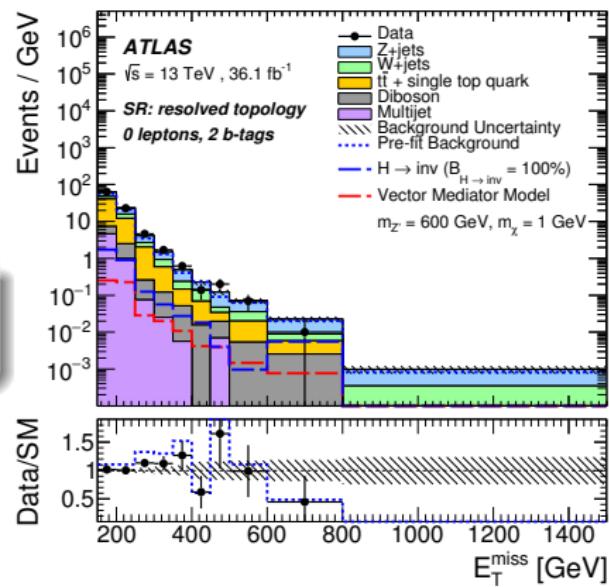
Bin according to number of b -tags and jet substructure variables.

$$\mathcal{B}_{\text{inv}} < 0.83 \text{ at 95% CL}$$
$$(\text{exp: } 0.58^{+0.23}_{-0.16})$$

Backgrounds

Mostly $V + \text{jets}$ and $t\bar{t}$.

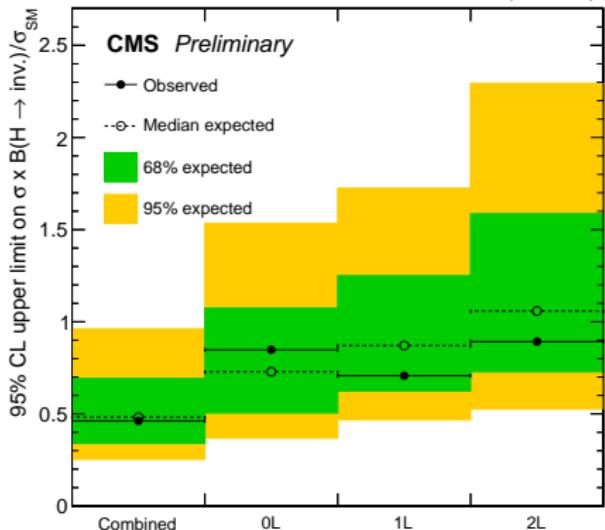
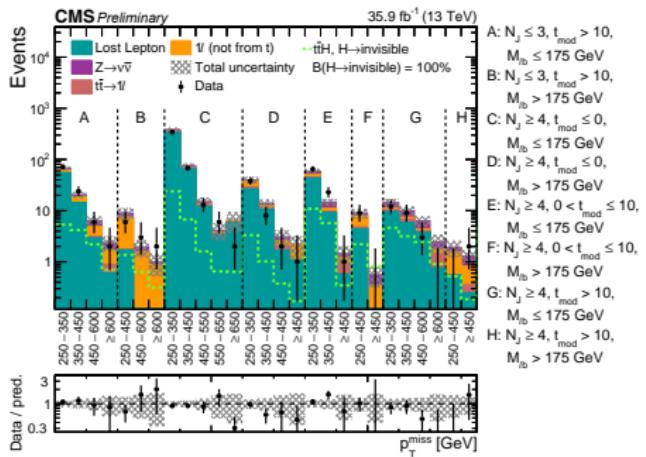
Constrained using CRs containing leptons.



Discriminating variables:

- all-had: E_T^{miss}
- $\ell + \text{jets}$: m_T
- $\ell\ell$: m_{T2}

$$= \min_{p_T^{\text{miss},1} + p_T^{\text{miss},2} = p_T^{\text{miss}}} [\max(m_T^1, m_T^2)]$$



95% CL limits obs (exp) (36 fb⁻¹)

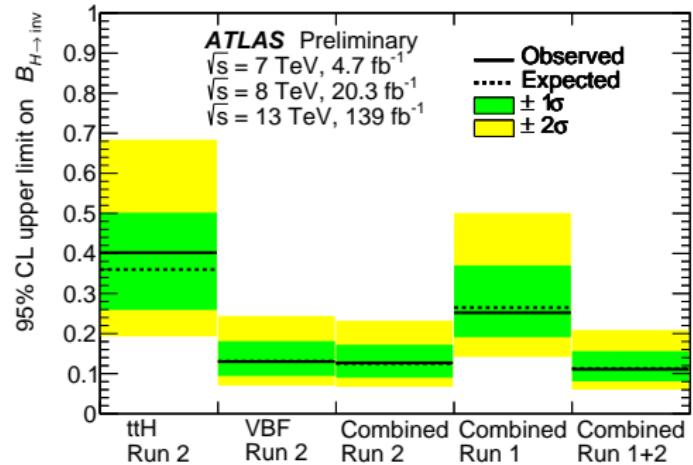
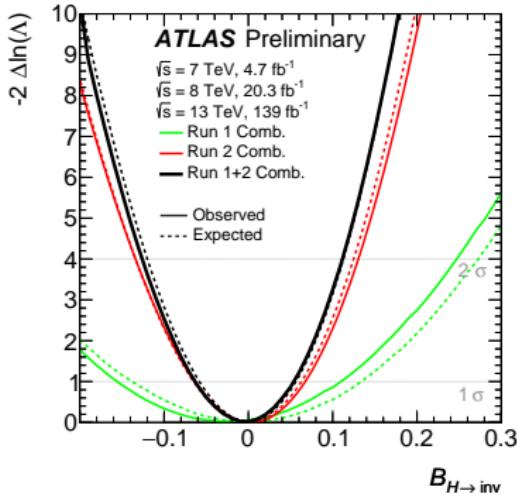
all-had: $\mathcal{B}_{\text{inv}} < 0.85$ (0.73)

$\ell + \text{jets}$: $\mathcal{B}_{\text{inv}} < 0.71$ (0.87)

$\ell\ell$: $\mathcal{B}_{\text{inv}} < 0.89$ (1.06)

all: $\mathcal{B}_{\text{inv}} < 0.46$ (0.48)

$H \rightarrow$ invisible: Combination

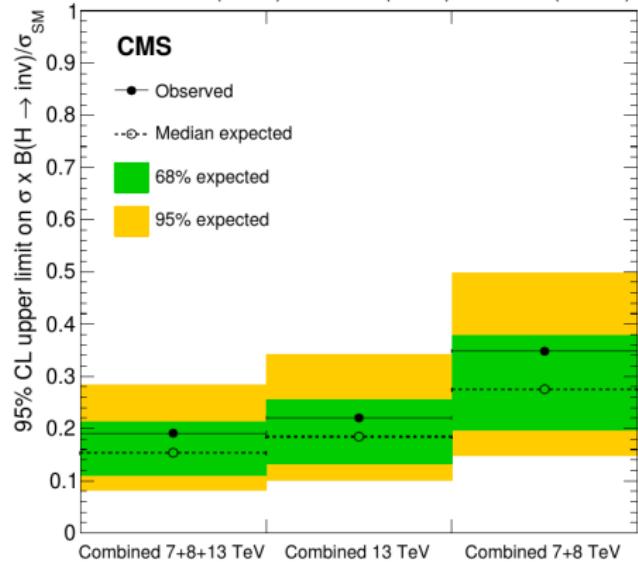


Run 2: $B_{\text{inv}} < 0.13$ at 95% CL (exp: $0.12^{+0.05}_{-0.04}$)

Run 1+2: $B_{\text{inv}} < 0.21$ at 95% CL (exp: $0.11^{+0.04}_{-0.03}$)

$H \rightarrow \text{invisible}$: Combination

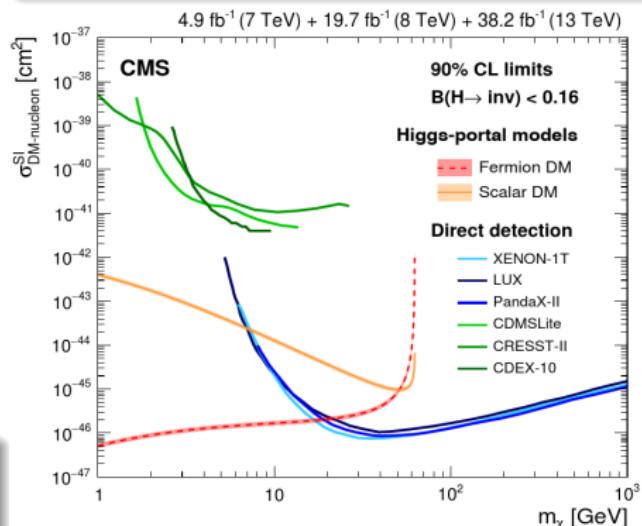
4.9 fb^{-1} (7 TeV) + 19.7 fb^{-1} (8 TeV) + 38.2 fb^{-1} (13 TeV)



95% CL; obs (exp)

Run 1+2015	0.23 (0.24)
2016	0.26 (0.20)
All	0.19 (0.15)

Higgs portal: interpret in terms of WIMP mass and nuclear scattering cross section.

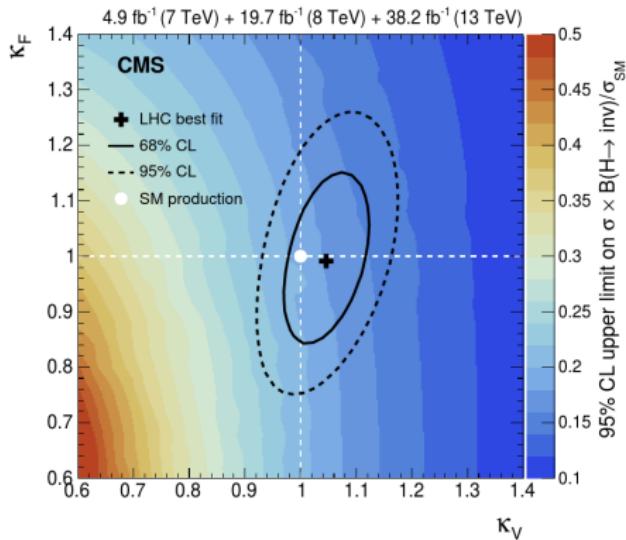
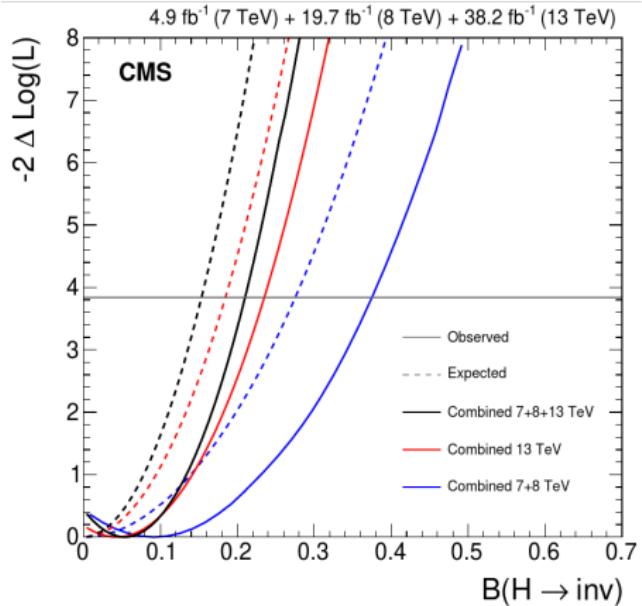


$\mathcal{B}_{\text{inv}} < 0.16$ at 90% CL

$H \rightarrow$ invisible: Combination



[arXiv:1809.05937]



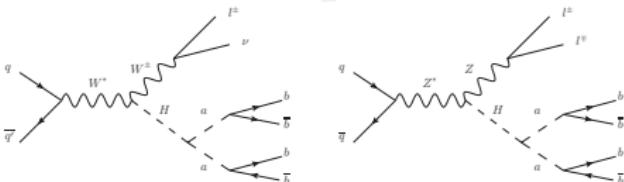
Run 2 (2016): $\mathcal{B}_{\text{inv}} < 0.26$ at 95% CL (exp: 0.20)

Run 1+2: $\mathcal{B}_{\text{inv}} < 0.19$ at 95% CL (exp: 0.15)

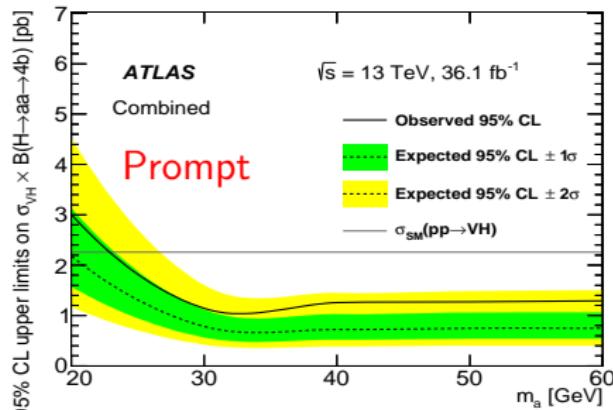
$VH \rightarrow Vaa \rightarrow (\ell\ell/\ell\nu) bbbb$ (resolved)

Searching for H produced with W/Z .
 H decays via $aa \rightarrow bbbb$ either promptly or with $c\tau$ up to 6 mm.

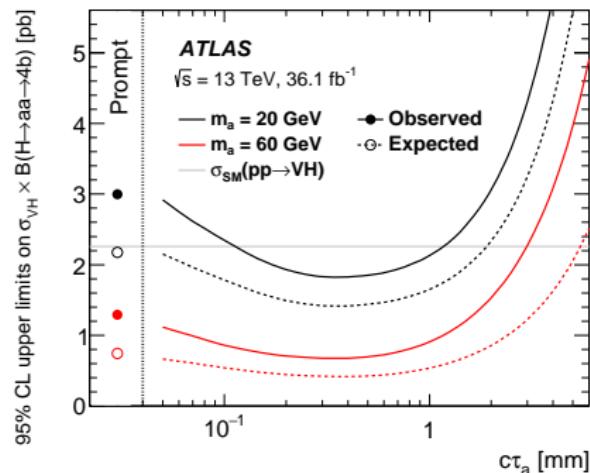
Pair b -jets to minimize $m_{bb1} - m_{bb2}$.
 Train BDTs for a masses of 20, 30, and 50 GeV for signal against $t\bar{t}$ and $Z + \text{jets}$ backgrounds.
 Fit BDT outputs to signal+bkg.



Require W/Z decay and ≥ 3 b -tags.



Lose sensitivity for $m_a < 30$ GeV because jets start to merge.



$ZH \rightarrow Zaa \rightarrow (\ell\ell) bbbb$ (merged)



[arXiv:1806.07355]

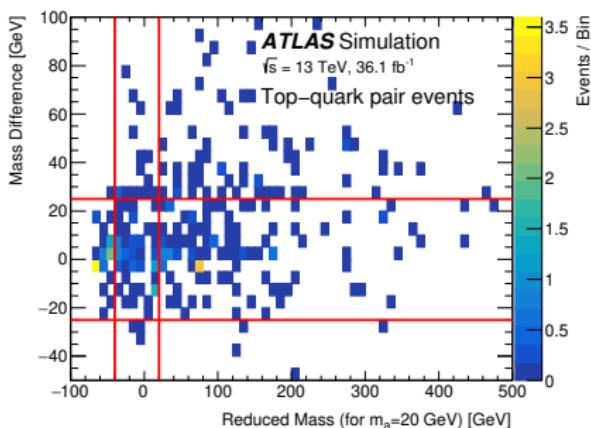
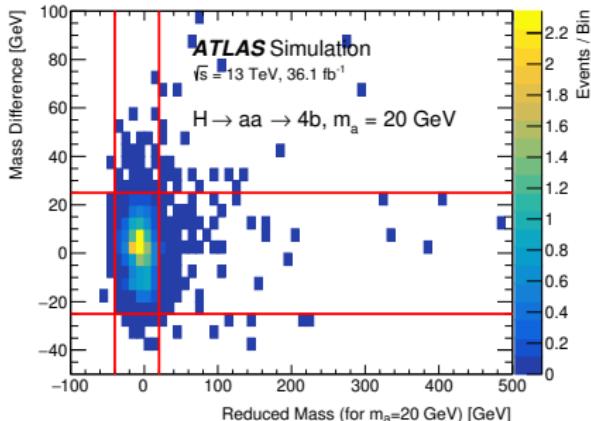
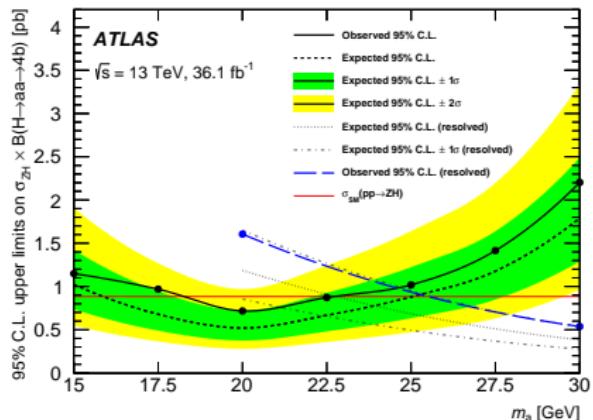
$$85 < m_{\ell\ell} < 100 \text{ GeV}$$

Dedicated $b\bar{b}$ pair reconstruction:
Reclustering of large- R jets
BDT discrimination

$$|m_{a1} - m_{a2}| < 25 \text{ GeV}$$

Overall mass consistent with $H(125)$

Background primarily $t\bar{t}$ and $Z + \text{jets}$.
Constrained with CRs.



VBF $H \rightarrow aa \rightarrow \gamma\gamma gg$

If fermionic decay is suppressed, a can have significant decays to g/γ .

Tag H production using VBF.

2 photons, ≥ 4 jets

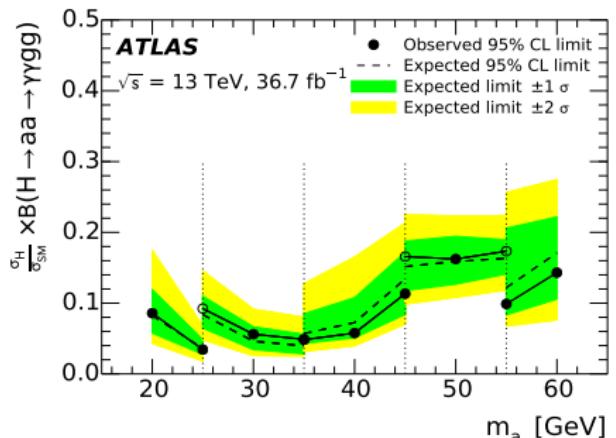
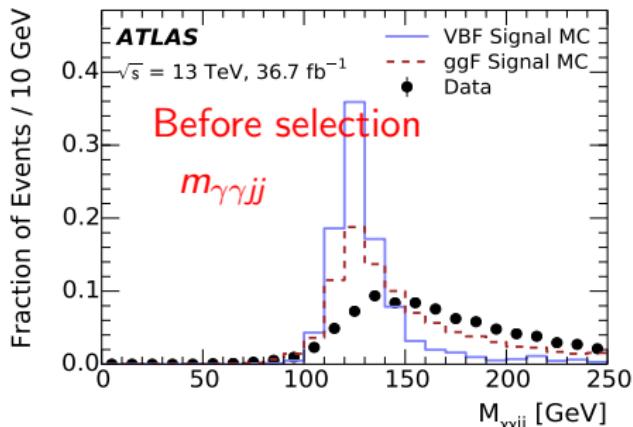
$$m_{jj}^{\text{VBF}} > 500 \text{ GeV}$$

$$100 < m_{\gamma\gamma jj} < 150 \text{ GeV}$$

$$|m_{jj} - m_{\gamma\gamma}| < 12\text{--}24 \text{ GeV}$$

Bkg estimated from data sidebands (ABCD).

m_a	N_{evt}	N_{bkg}
20–25	4	6^{+7}_{-4}
25–35	15	8^{+7}_{-4}
35–45	26	36^{+23}_{-14}
45–55	38	26^{+22}_{-12}
55–60	36	66^{+56}_{-28}



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



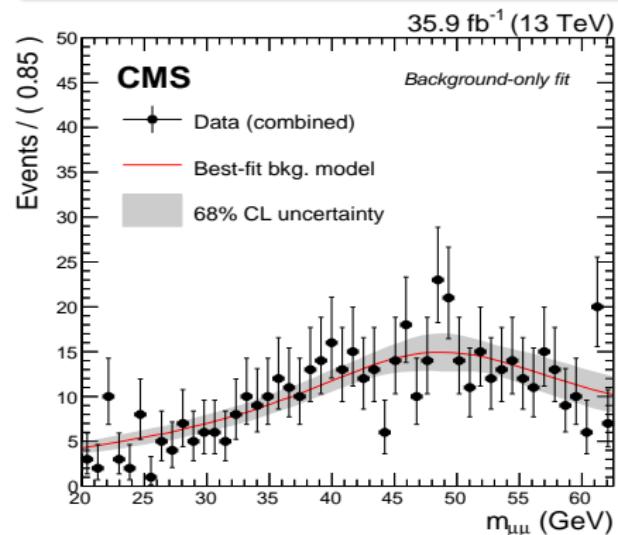
[arXiv:1812.06359]

35.9 fb^{-1} (13 TeV)

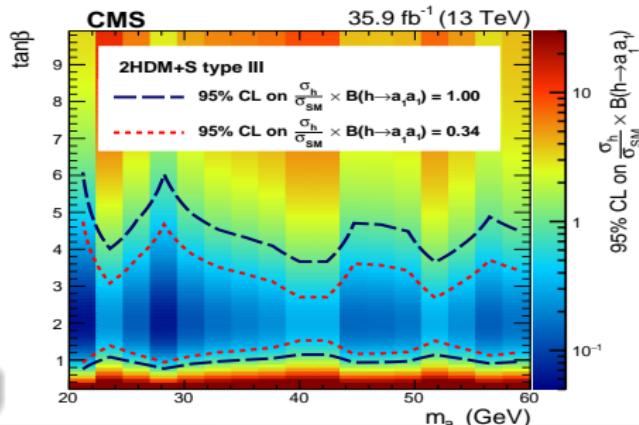
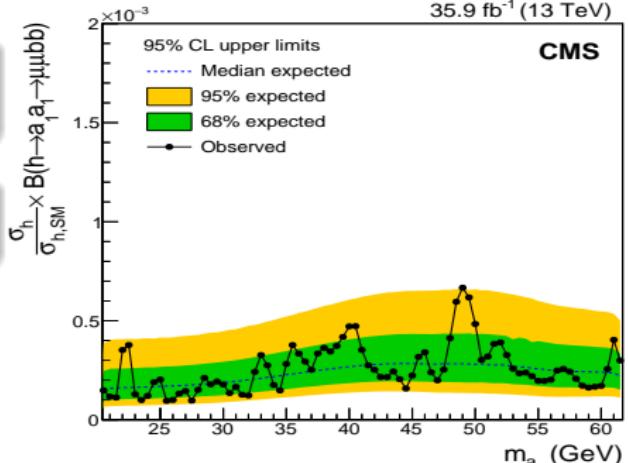
$\mu^+\mu^-$ with $20 < m_{\mu\mu} < 62.5$ GeV.

Exactly 2 b -tags; $E_T^{\text{miss}} < 60$ GeV

$$\chi^2 = \frac{(m_{bb} - m_{\mu\mu})^2}{\sigma_{bb}^2} + \frac{(m_{\mu\mu bb} - 125)^2}{\sigma_h^2} < 5$$



Extract signal via unbinned fit to $m_{\mu\mu}$.



$h \rightarrow \mu\mu\mu\mu$



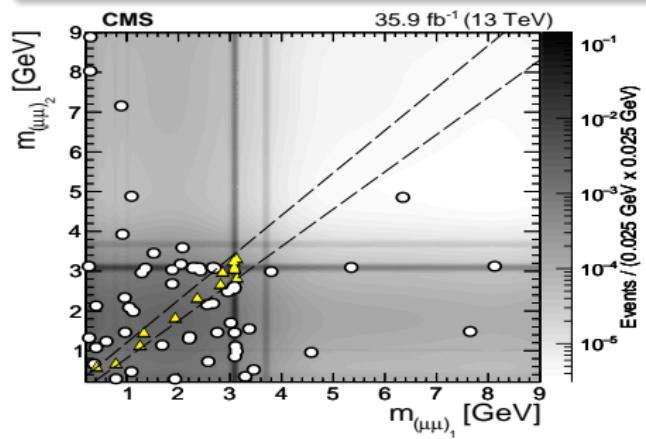
[arXiv:1812.00380]

Search for $h \rightarrow aa + X \rightarrow \mu\mu\mu\mu + X$.

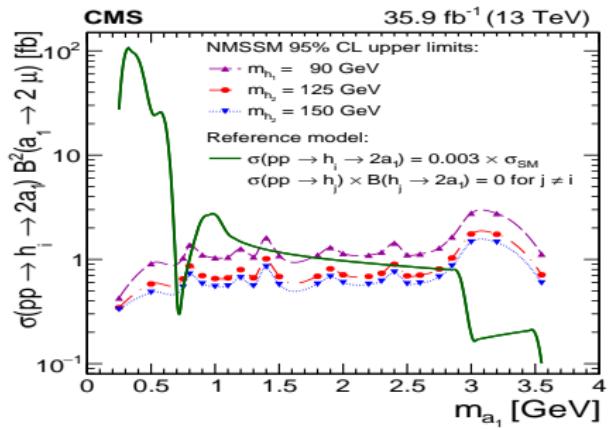
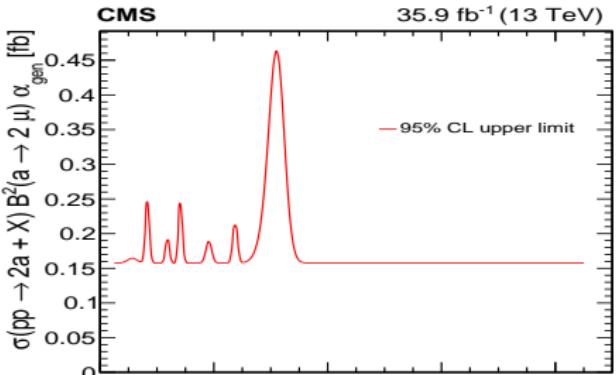
h may or may not be SM Higgs.

2 $\mu\mu$ pairs, $m_{\mu\mu} < 9$ GeV.

$m_{\mu\mu 1}$ and $m_{\mu\mu 2}$ consistent.



Dominant bkg: $b\bar{b}$, double- J/ψ , VV . Observe 13 evts, expect $9.90 \pm 1.24 \pm 1.84$.



$H \rightarrow aa \rightarrow bb\tau\tau/\mu\mu\tau\tau$

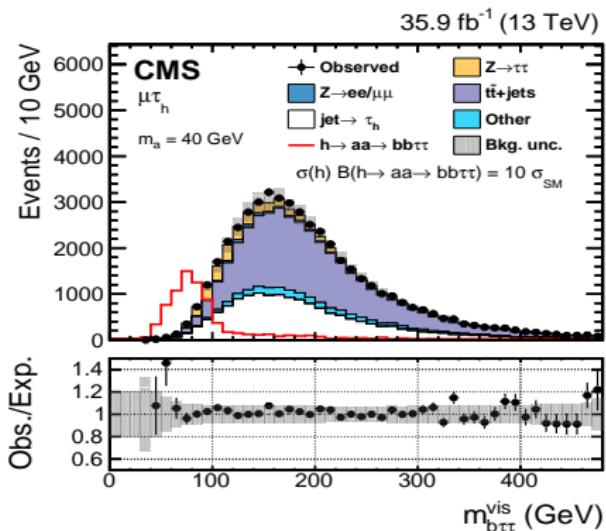


[arXiv:1805.10191]
[arXiv:1805.04865]

Final states: $e\mu, \mu\tau_h, e\tau_h$

At least one b -tag.

Categorize based on $m_{bb\tau\tau}^{\text{vis}}$;
additional kinematic selection.

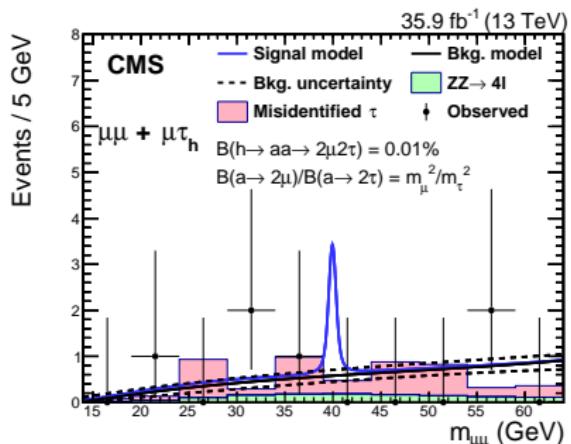


Extract signal using $m_{\tau\tau}^{\text{vis}}$

Estimate bkg with simulation + fake factor.

Final states: $\mu\mu + (e\mu, \mu\tau_h, e\tau_h, \tau_h\tau_h)$

$m_{\mu\mu\tau\tau}^{\text{vis}} < 100\text{--}130 \text{ GeV}; \quad m_{\tau\tau}^{\text{vis}} < m_{\mu\mu}$



Search for peak in $m_{\mu\mu}$.

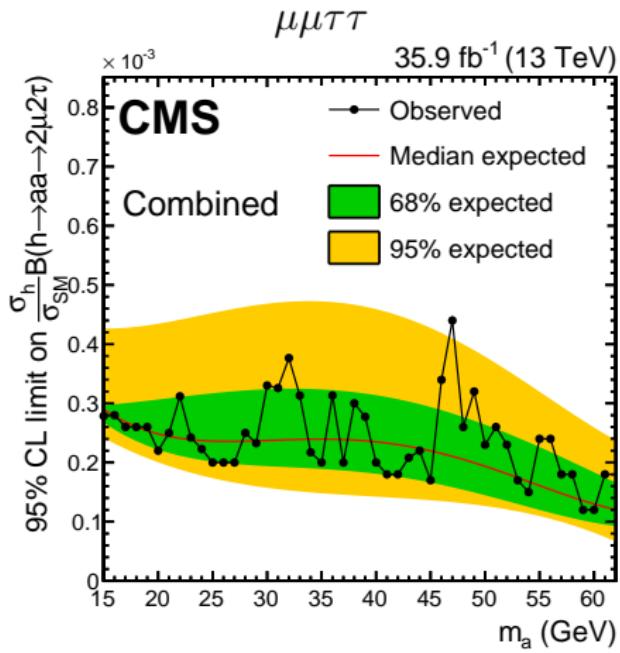
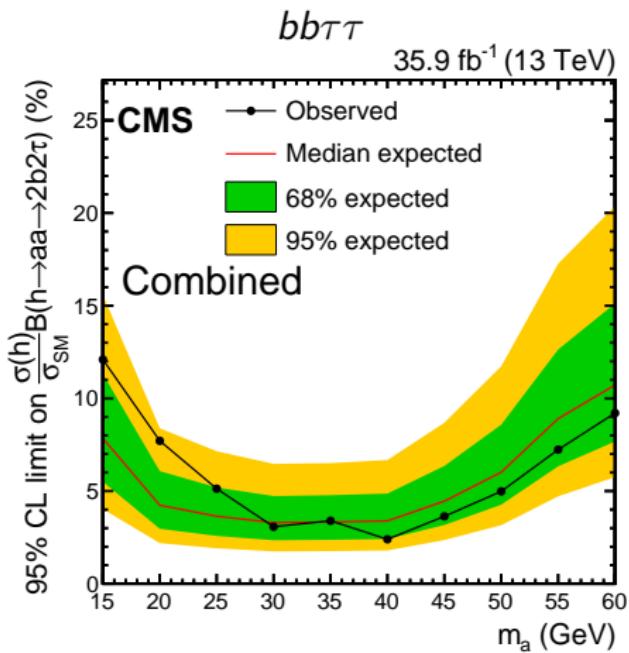
Bkg: Mostly ZZ and Z/WZ + jets with misidentified τ, estimated with simulation + fake factor.

$$H \rightarrow aa \rightarrow bb\tau\tau/\mu\mu\tau\tau$$



[arXiv:1805.10191]
[arXiv:1805.04865]

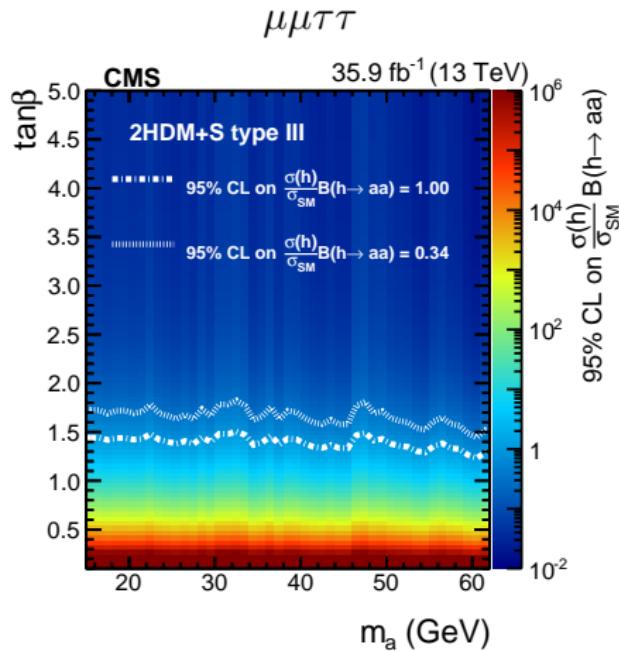
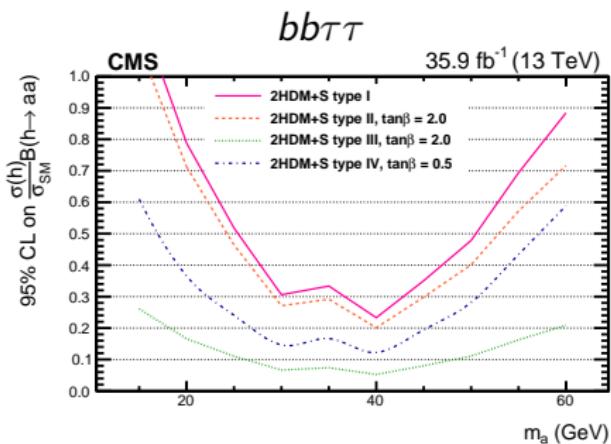
Model-independent limits on $\frac{\sigma_H}{\sigma_{SM}} \mathcal{B}(H \rightarrow aa \rightarrow bb\tau\tau/\mu\mu\tau\tau)$.



$$3\% < \mathcal{B}(H \rightarrow aa \rightarrow bb\tau\tau) < 12\%$$

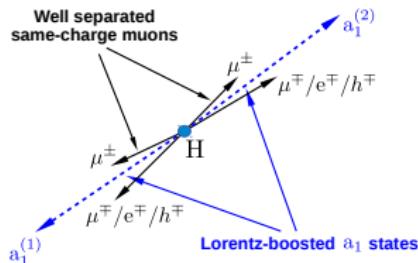
$$12\% < \mathcal{B}(H \rightarrow aa \rightarrow \mu\mu\tau\tau) < 30\%$$

Model-dependent limits on $\frac{\sigma_H}{\sigma_{SM}} \mathcal{B}(H \rightarrow aa)$ for NMSSM models.

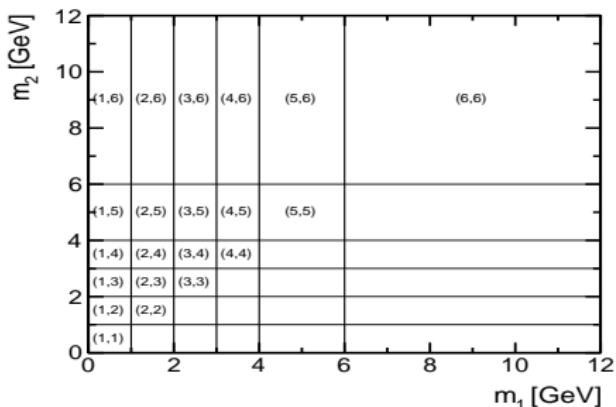


$$h \rightarrow aa \rightarrow \tau\tau\tau\tau/\tau\tau\mu\mu$$

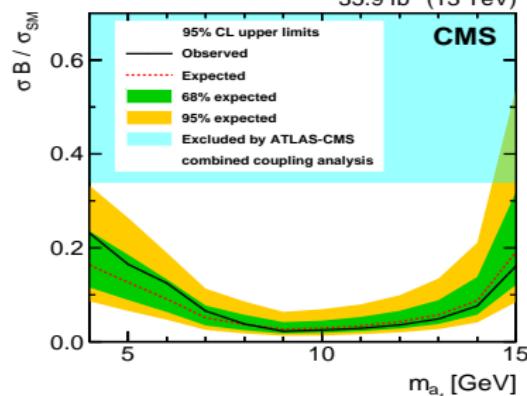
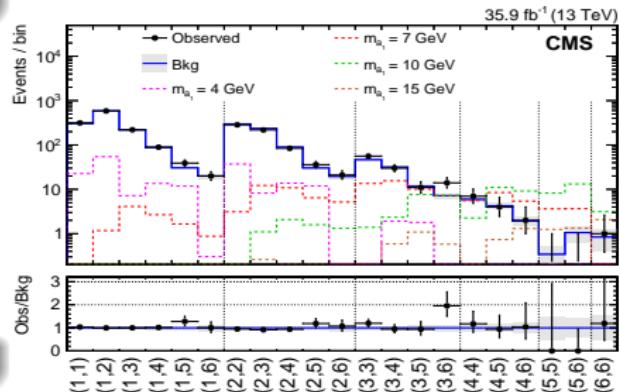
Require SS, widely-separated μ pair, each with a nearby OS track.



Plot masses of the two pairs and bin in 2D.



Background mostly QCD multijets.

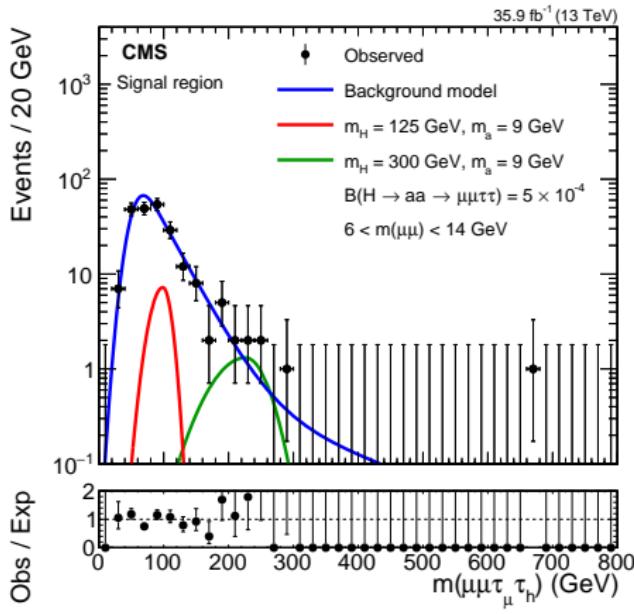


$H \rightarrow aa \rightarrow \mu\mu\tau\tau$ (boosted)

Dedicated reconstruction algorithm for close-by $\tau_\mu\tau_h$ allows probing smaller m_a .

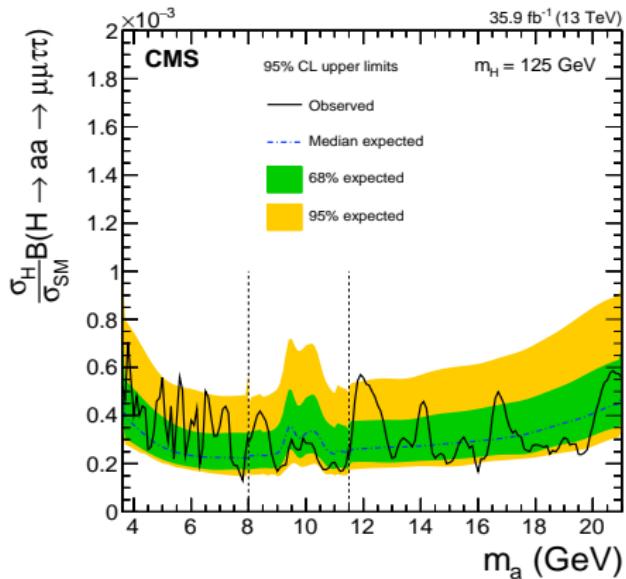
$\mu^+\mu^-$ pair with $\Delta R < 1$

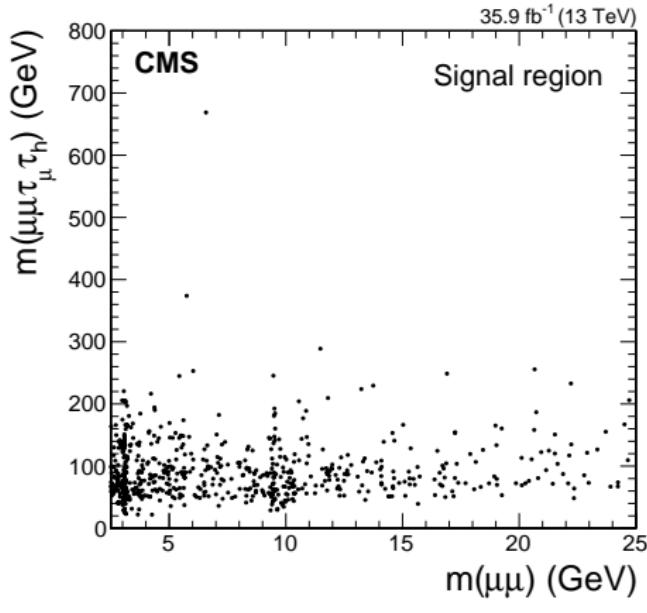
$\tau_\mu\tau_h$ pair with $\Delta R < 0.8$



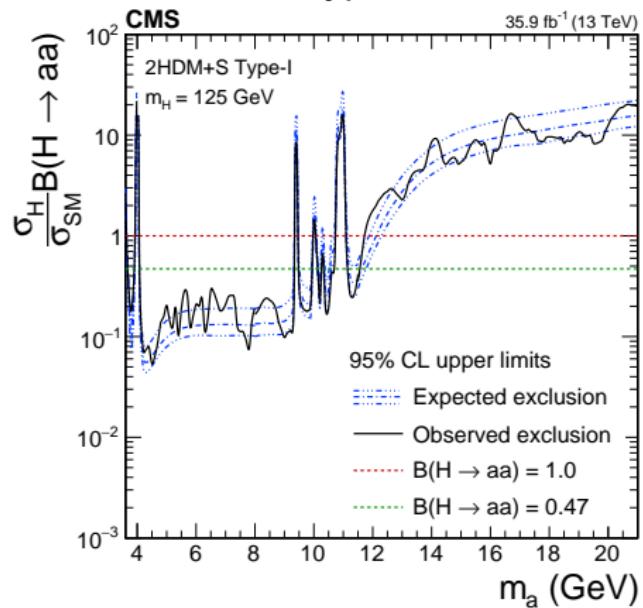
Background mostly $\Psi/\Upsilon + \text{jets}$

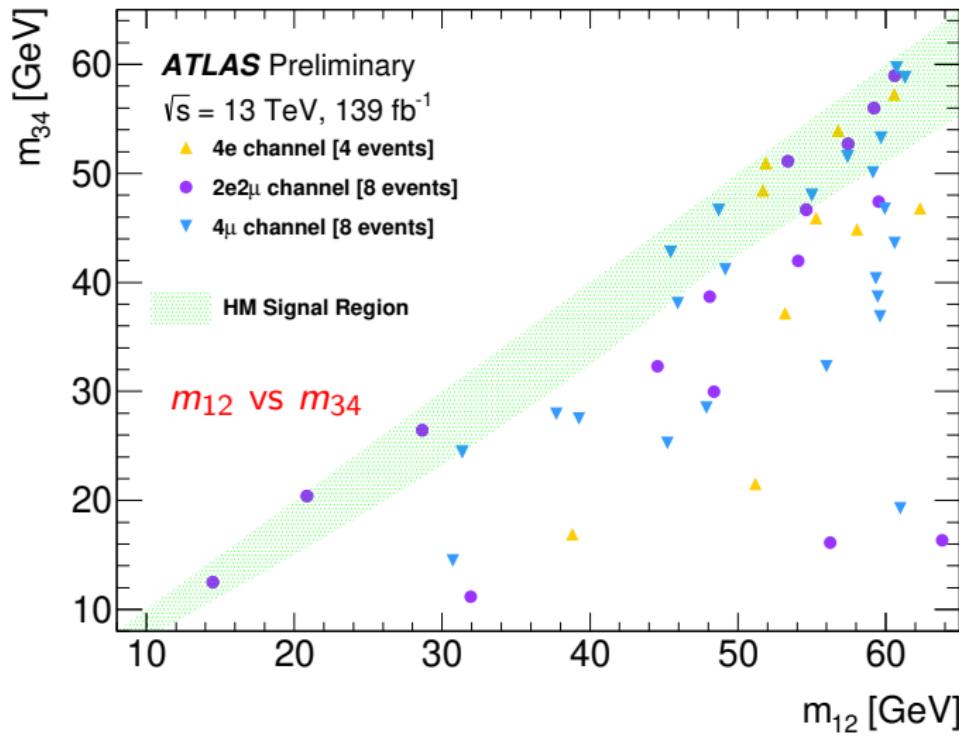
Unbinned fit to $m(\mu\mu)$ vs. $m(\mu\mu\tau_\mu\tau_h)$ in signal + CRs.



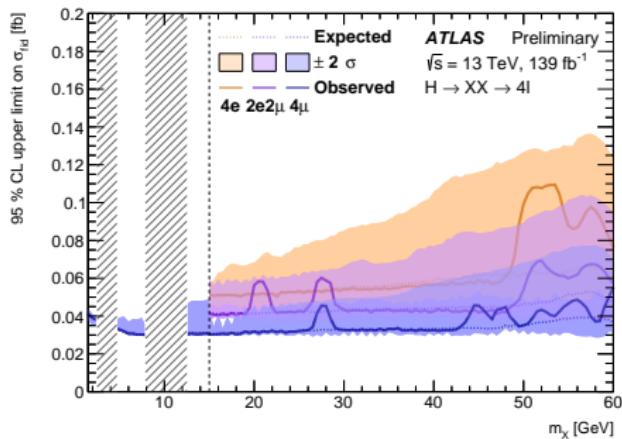
$m(\mu\mu)$ vs. $m(\mu\mu\tau_\mu\tau_h)$ 

Model-dependent branching ratio limit: 2HDM+S Type-I

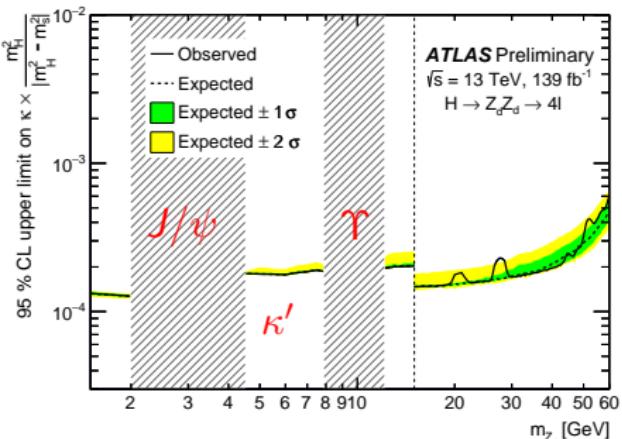




Model-independent fiducial
 $H \rightarrow XX \rightarrow 4\ell$ cross sections.

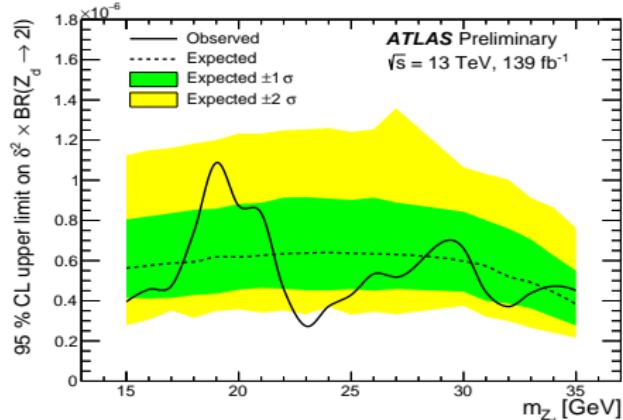
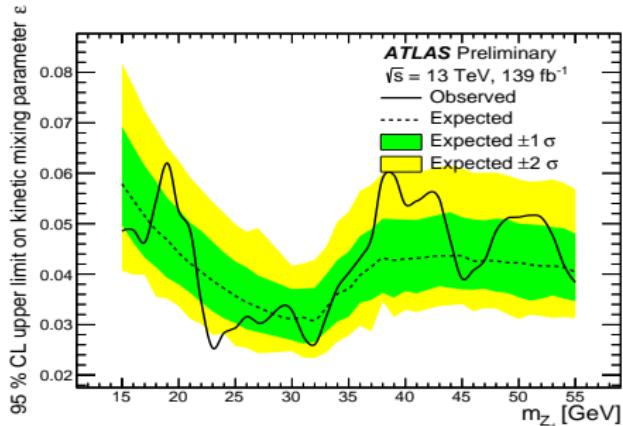
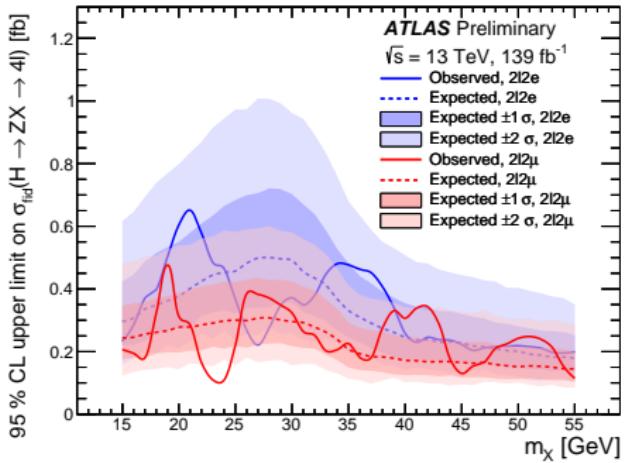


Limit on κ' mixing parameter.



$H \rightarrow ZZ_d/aa \rightarrow 4\ell$

Limits on fiducial $H \rightarrow ZX \rightarrow 4\ell$
cross section, ϵ , and
 $\delta^2 \times \mathcal{B}(Z_d \rightarrow \ell\ell)$.



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



[CMS-PAS-HIG-19-007]

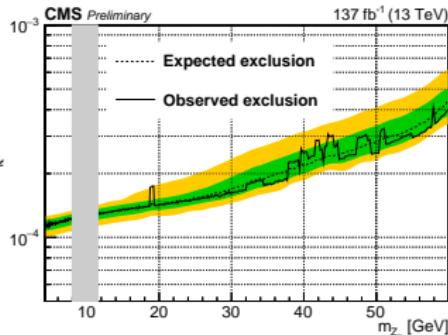
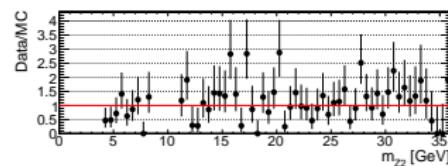
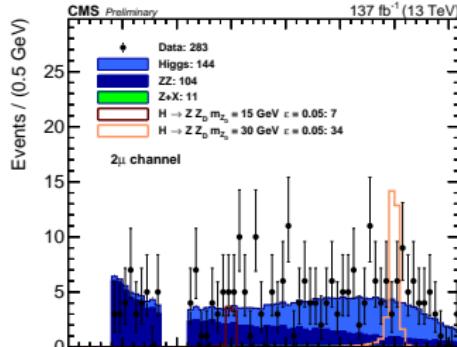
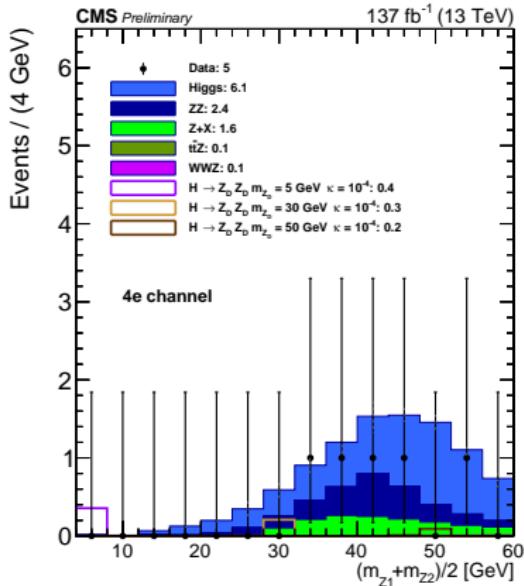
Two ℓ pairs.

$m_{4\ell}$ consistent with m_H .

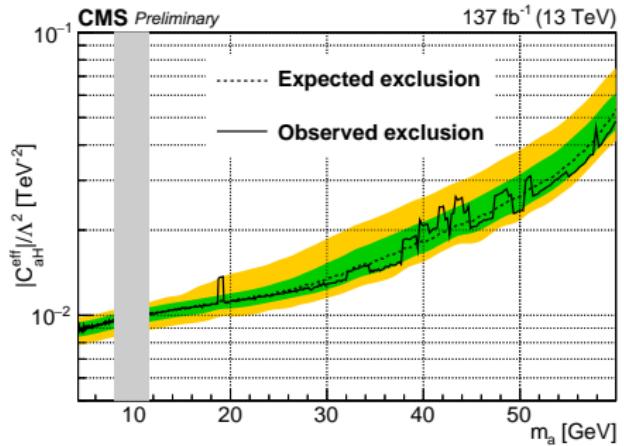
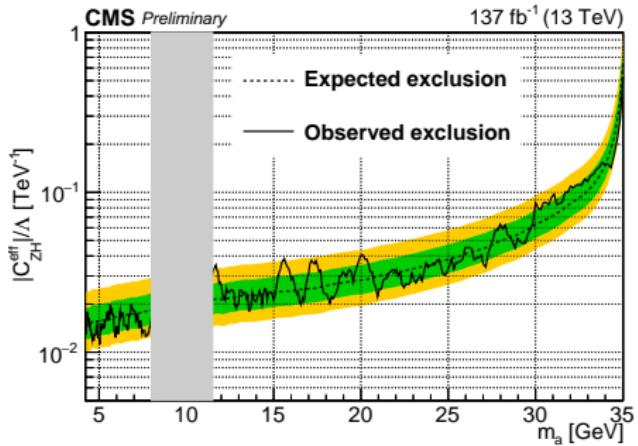
$m_{\ell\ell\ell}$ inconsistent with Υ .

XX: Minimize mass difference between pairs.

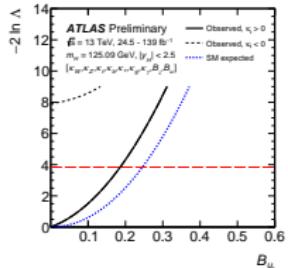
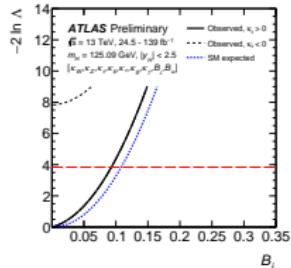
ZX: Higher-mass pair closest to m_Z . Must be > 40 GeV.



Axion interpretation limits.



Run 2 ATLAS \mathcal{B}_{BSM} limits



Parameter	(a) $B_i = B_u = 0$	(b) B_i free, $B_u \geq 0$, $\kappa_{W,Z} \leq 1$
κ_Z	1.02 ± 0.06	> 0.88 at 95% CL
κ_W	1.06 ± 0.07	> 0.89 at 95% CL
κ_b	$0.98^{+0.14}_{-0.13}$	0.92 ± 0.10
κ_t	1.00 ± 0.12	0.97 ± 0.12
κ_τ	$1.05^{+0.15}_{-0.14}$	$1.02^{+0.13}_{-0.14}$
κ_γ	$1.06^{+0.08}_{-0.07}$	$1.04^{+0.06}_{-0.07}$
κ_g	$0.96^{+0.09}_{-0.08}$	$0.93^{+0.08}_{-0.07}$
B_i	-	< 0.09 at 95% CL
B_u	-	< 0.19 at 95% CL

