Low Mass Higgs Boson Searches from ATLAS and CMS

Higgs Couplings 2018
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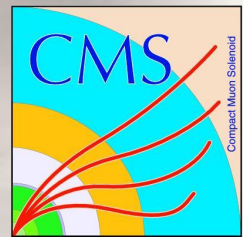
(on behalf of the ATLAS & CMS Collaborations)



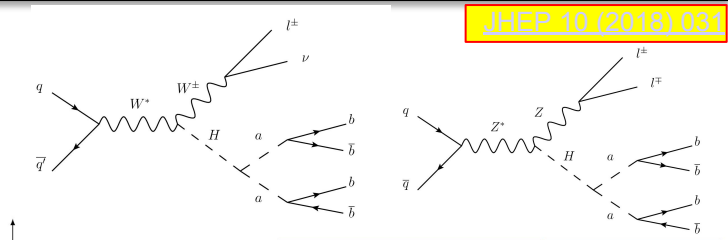
Motivation

- Very narrow Higgs boson width (Γ~4 MeV, $\Gamma/m_H = O(10^{-5})$) provides strong sensitivity to new physics $\Longrightarrow$ even small couplings of BSM particles to the Higgs boson (H) can lead to sizable B($H \rightarrow$BSM)
  - O(1%) coupling to a singlet scalar field s can give B($H \rightarrow ss$) = O(10%)!
- Non-SM decays of the Higgs boson can be inferred from couplings measurements in the visible Higgs decay channels
  - e.g. ATLAS Run-2 measurement w/ 80 fb^{-1}: $B_{BSM} < 26\%$ (ATLAS-CONF-2018-031)
  - Or, B_{BSM} can be directly measured by observing $H \rightarrow ss \rightarrow$?? ….
- New scalars are a part of many BSM models
  - While there are many searches for heavy (>125 GeV) BSM particles, possible light BSM particles are not (yet!) well explored at colliders
  - The Higgs boson is a well-motivated portal to other BSM sectors (e.g. 2HDM+S interpretations in this talk) and represents a new tool for further discovery!

$H(125) \rightarrow aa \rightarrow bbbb$

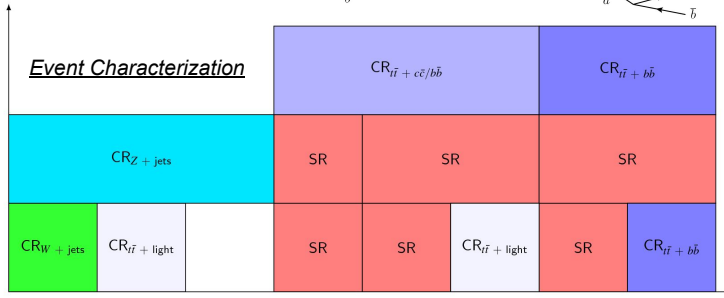
JHEP 10 (2018) 031

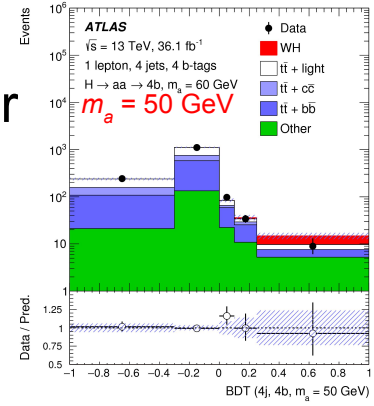
If a pseudoscalar *a*-boson mixes with the Higgs boson and inherits its Yukawa couplings, then $a \rightarrow bb$ decays would be dominant for $m_a > 2m_b$

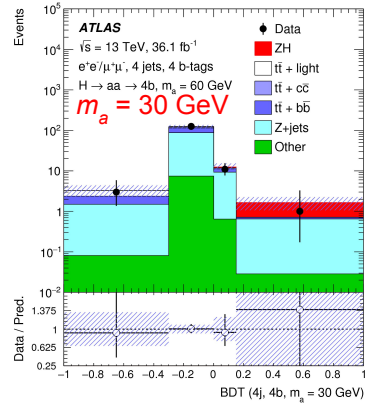


Analysis Overview

- Search using Higgs bosons produced in association with a vector boson
  - Final-state leptons provide a signature for trigger and background suppression
- Dominant backgrounds: $t\bar{t}$+jets and *V*+jets
- BDT classifier used as a signal discriminant





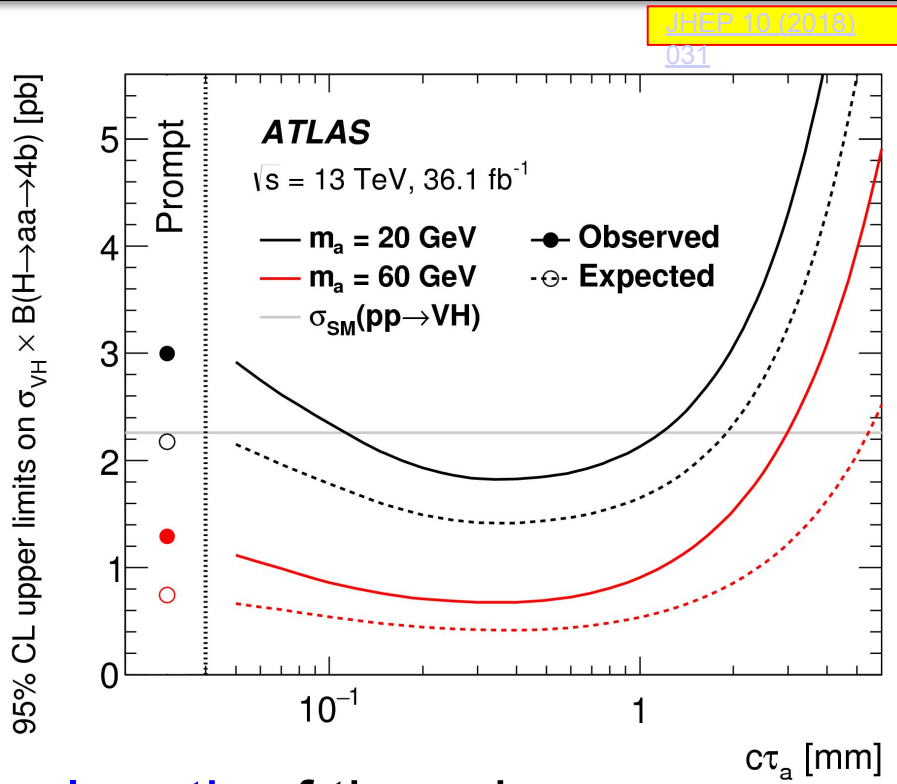


$H(125) \rightarrow aa \rightarrow bbbb$

- No significant excess over SM prediction is observed
- Limits set as a function of m_a and $c\tau_a$ for

  $\sigma(pp \rightarrow VH) \times BR(H \rightarrow aa \rightarrow bbbb)$

  and compared to the SM inclusive Higgs cross section $\sigma(pp \rightarrow VH)$



- In some models, the proper decay length of the *a*-boson is from 10μm to kilometers

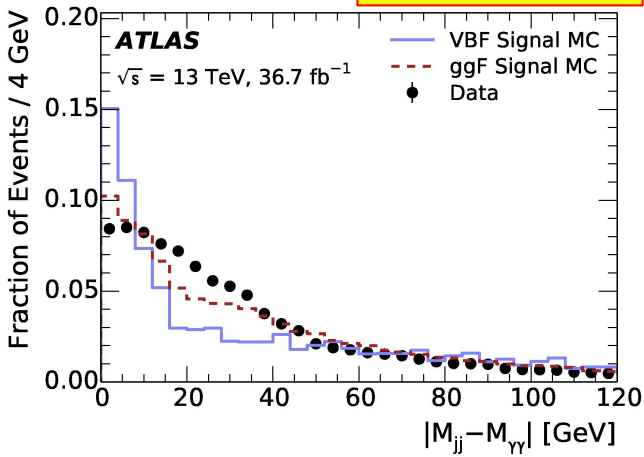
$H(125) \rightarrow aa \rightarrow \gamma\gamma jj$

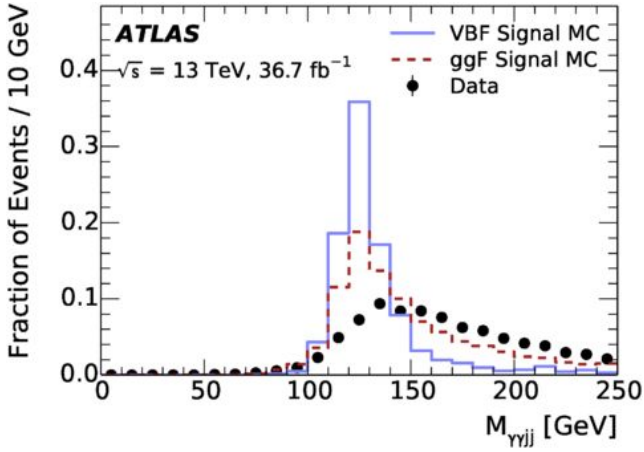
PRL B 782 (2018) 750

Motivated by models where fermionic decays of the a-boson are suppressed ($a \rightarrow \gamma\gamma/gg$ only)

Analysis Overview

- Focus on VBF production mode to suppress backgrounds (require ≥ 4 jets)
- Trigger on di-photons
- Requirements on p_T^{j1}, m_{jj}^{VBF}, $m_{\gamma\gamma jj}$, $|m_{jj} - m_{\gamma\gamma}|$
- Dominant background is $\gamma\gamma$+jets which is estimated using data-driven methods
- Signal extracted using counts in two uncorrelated observables in (di-)photon ID





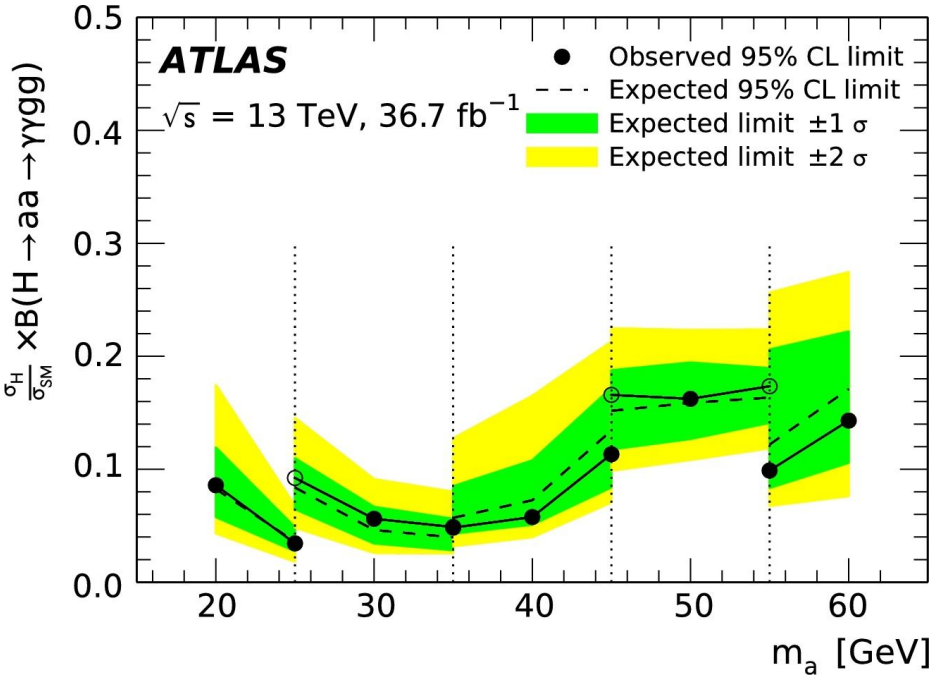
$H(125) \rightarrow aa \rightarrow \gamma\gamma jj$

PRL B 782 (2018) 750

- No significant excess over SM prediction is observed
- Limits set on

  $\sigma(pp \rightarrow H) \times \mathrm{BR}(H \rightarrow aa \rightarrow \gamma\gamma gg)$

  as a function of m_a, normalized to the SM inclusive Higgs cross section $\sigma(pp \rightarrow H)$:



$\sigma(pp \rightarrow H) \times \mathrm{BR}(H \rightarrow aa \rightarrow \gamma\gamma gg)$: 3.1 — 9.0 pb

$H(125) \to aa / Z_{(d)} Z_d \to \ell\ell\ell\ell$

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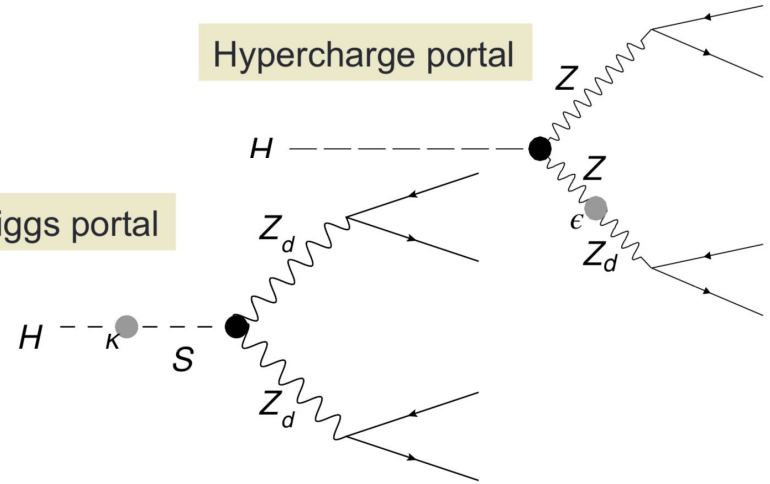
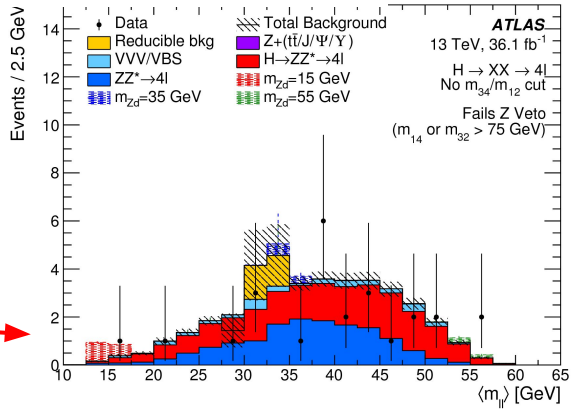
Search for a-boson through $H \to aa$ or Z_d: vector boson of dark sector $U(1)_d$

Analysis Overview

- Use combinations of lepton triggers
- Require 2 pairs of same-flavor, opposite-sign leptons (e/μ), Higgs mass window cut on $m(4\ell)$
- Backgrounds: $H \to ZZ^* \to 4\ell$ and $ZZ^* \to 4\ell$
  - Estimated using simulation, validated in background-enriched regions





$H(125) \to aa / Z_{(d)} Z_d \to \ell\ell\ell\ell$

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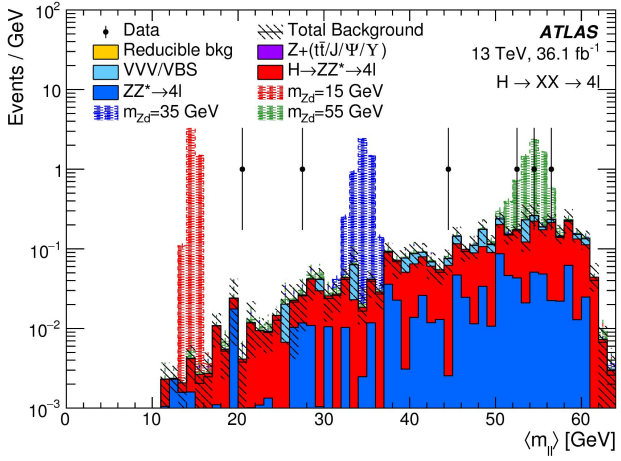
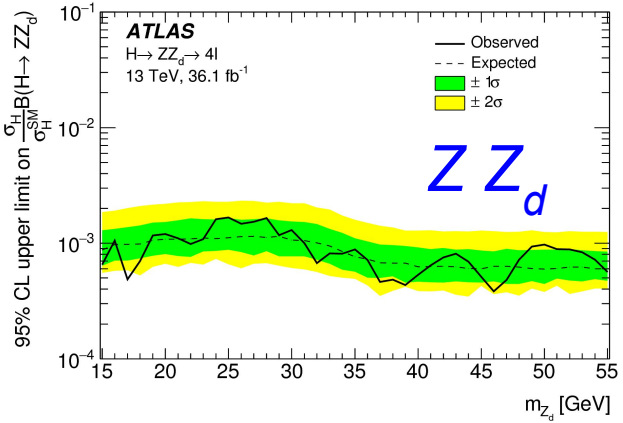
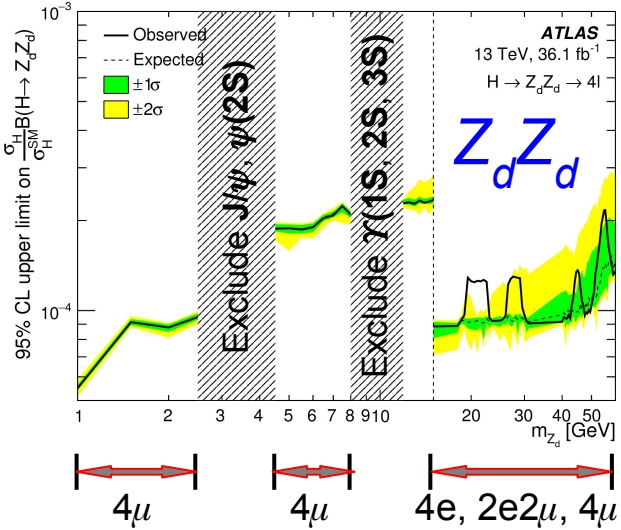
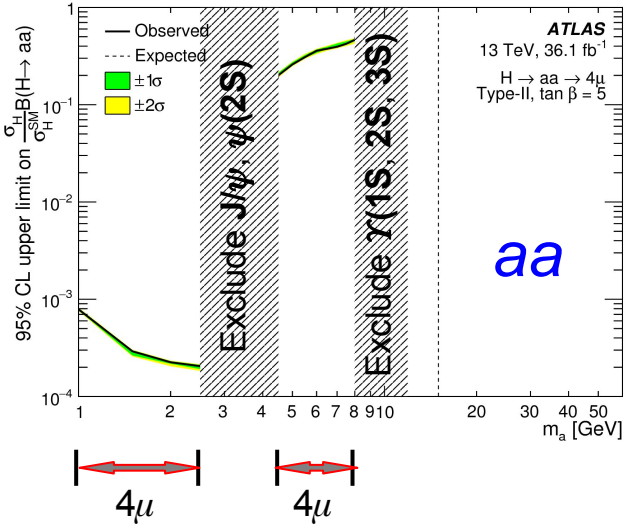




- No significant excess over SM prediction is observed
- Limits set on $H \to aa$ and $H \to Z_{(d)} Z_d$ as a function of $m(a)$ and $m(Z_d)$





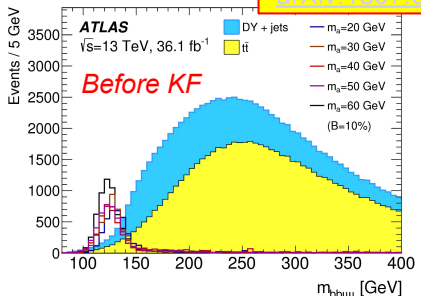
$H(125) \rightarrow aa \rightarrow bb\mu\mu$

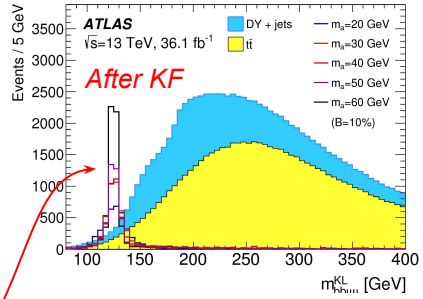
Motivated by lepton-specific BSM models where *a*-boson decays to muons are sizable (e.g. type-III 2HDM+*S*)

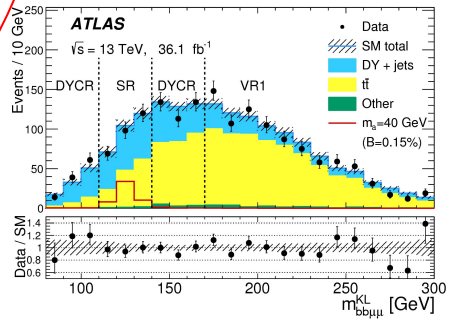
Analysis Overview

- Signature: 2μ + 2 *b*-tagged jets
- Single μ trigger: p_T > 24 to 26 GeV (run-dependent)
- Main backgrounds: DY($\mu\mu$) and $t\bar{t}$ production
  - m_H window, E_T^{miss} < 60 GeV to suppress ttbar
- Use a kinematic kit (KF) which exploits the symmetry of $H \rightarrow aa$ decays
  - $m_{\mu\mu}$ mass resolution is 10x better than m_{bb}
  - Fit *b*-jet energies compatible with $m_{\mu\mu} \approx m_{bb}$

⇨ 2x improvement of $m_{bb\mu\mu}$ resolution





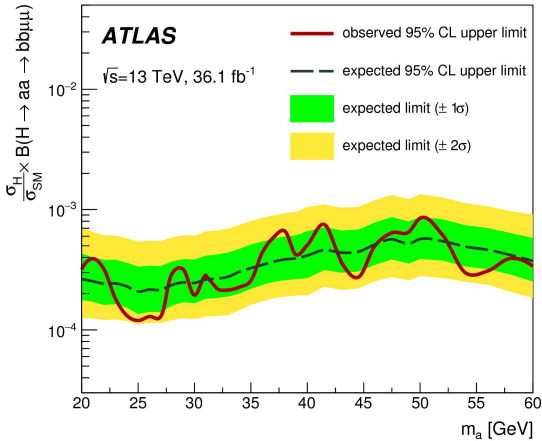


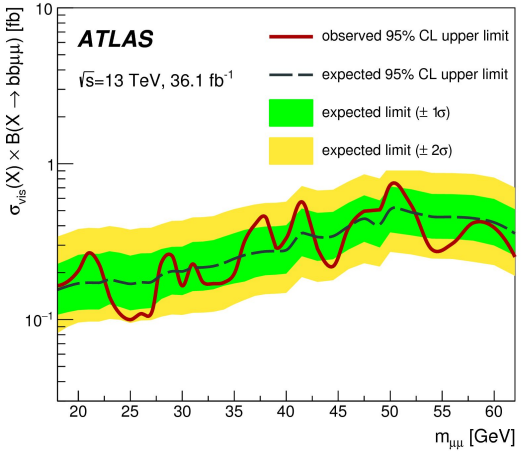
$H(125) \rightarrow aa \rightarrow bb\mu\mu$

arXiv:1807.00539

- No significant excess over SM prediction is observed
- Limits set for:
  - BR($H \rightarrow aa \rightarrow bb\mu\mu$) as a function of m_a, given the SM Higgs cross section:

    10^{-4} — 10^{-3} for m_a = [20, 60] GeV
  - Visible cross section for new physics times branching ratio to the $bb\mu\mu$ final state: 0.1 — 0.73 pb for m_a = [18, 62] GeV

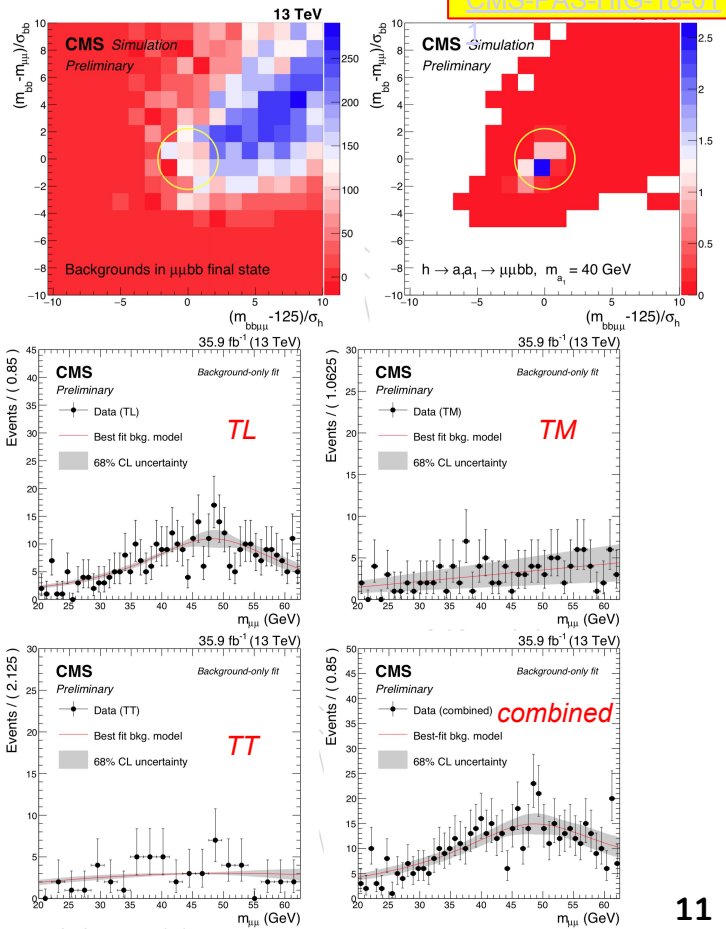




CMS-PAS-HIG-18-01

Analysis Overview

- Signature: 2μ + 2 b-tagged jets
- Di-μ trigger with p_T > 17 and 8 GeV
- Main backgrounds: DY($\mu\mu$) and ttbar production
  - E_T^{miss} < 60 GeV to suppress $t\bar{t}$
- Select events with $m_{\mu\mu} \simeq m_{bb}$ and $m_{bb\mu\mu} \simeq m_H$ through a $\chi^2 < 2$ cut with
  - $\chi^2 = (m_{bb} - m_{\mu\mu})^2/\sigma_{bb}^2 + (m_{bb\mu\mu} - 125\ GeV)^2/\sigma_H^2$
- Events categorized by b-tagging quality
  - TL, TM, TT (T=tight, M=medium, L=loose)

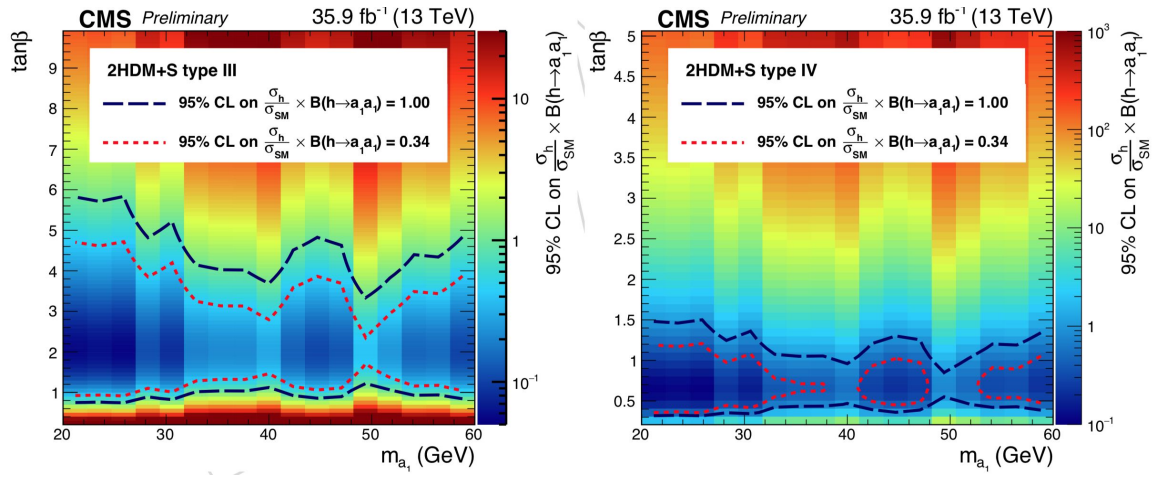


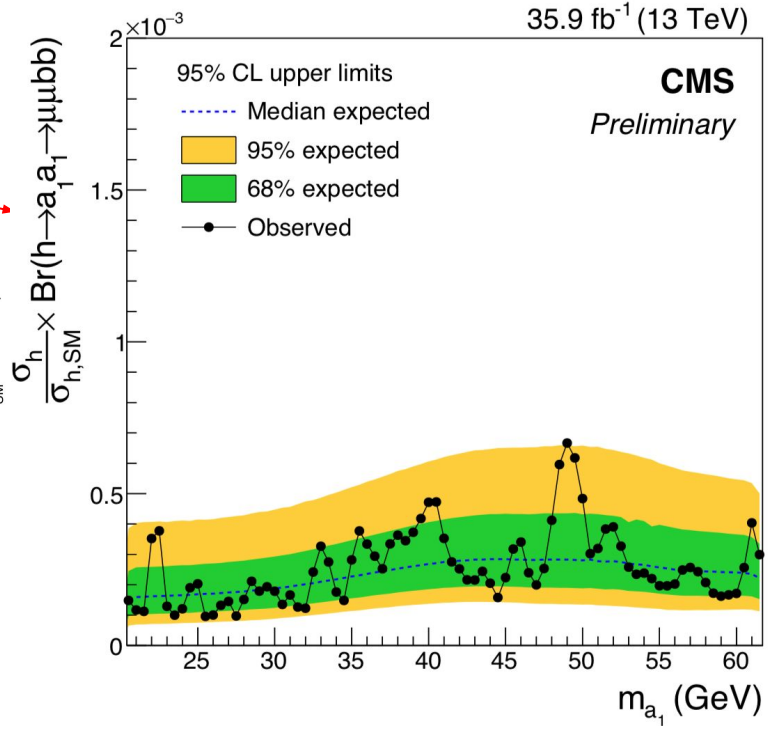
$H(125) \rightarrow aa \rightarrow bb\mu\mu$

NEW NEW

CMS-PAS-HIG-18-01

- No significant excess over SM prediction is observed
- BR Limits vary from 2×10^{-4} to 10^{-3} depending on m_a





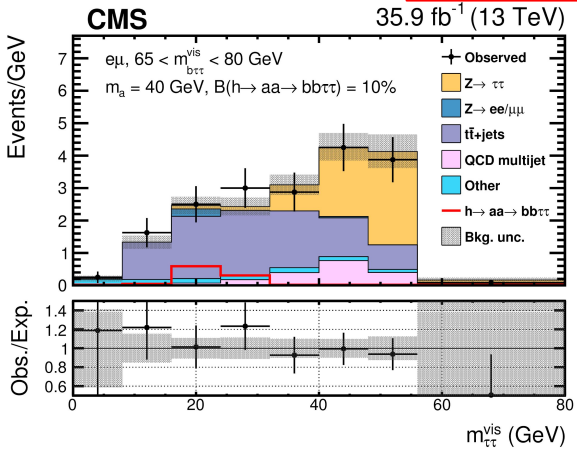
Also derived limits on type-III 2HDM+*S* considering $bb\tau\tau$ signal as $bb\mu\mu$ mis-ID

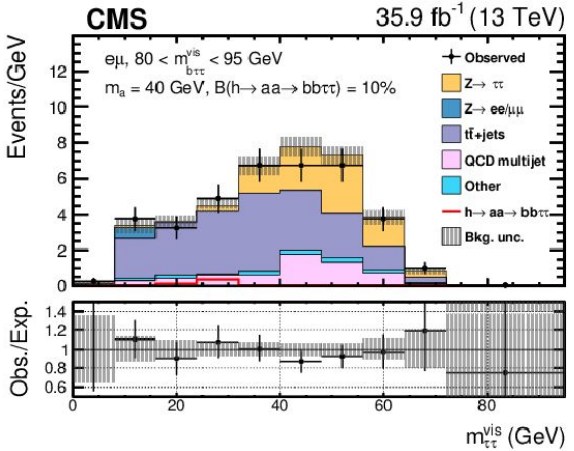
$H(125) \rightarrow aa \rightarrow bb\tau\tau$

arXiv:1805.10191

Analysis Overview

- Signature: 2τ + at least one *b*-jet
  - $\tau\tau$ categorized by $e\mu$, $e\tau_h$, $\mu\tau_h$
- Dominant backgrounds: DY($\tau\tau$) and $t\bar{t}$
  - Events with jet$\rightarrow\tau_h$ mis-id (from *W*+jets, top, QCD multijets production) are also significant
- Signal extracted with binned ML fit to $M^{vis}(\tau\tau)$ to probe m_a= [15, 60] GeV

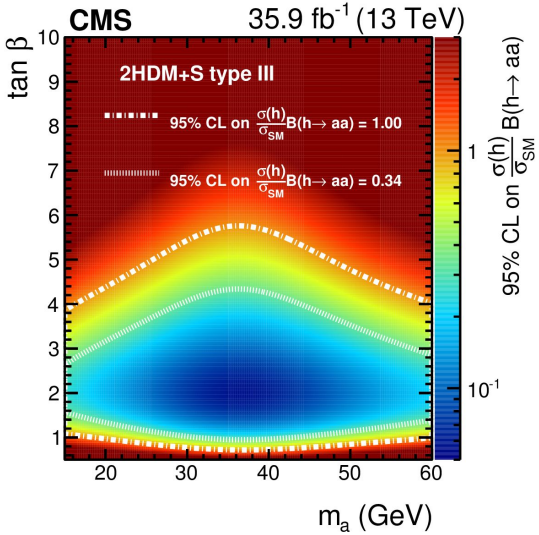


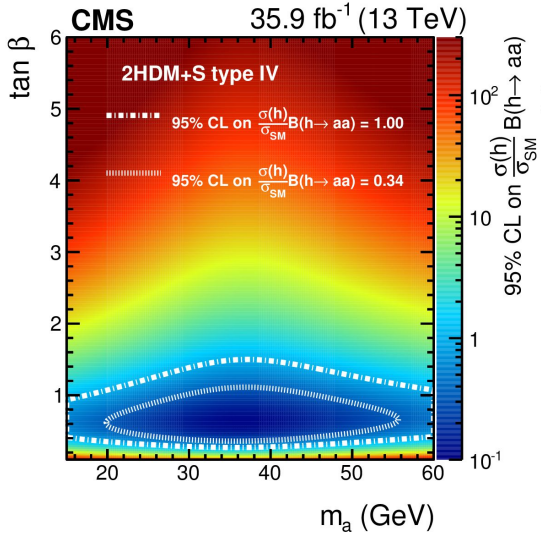


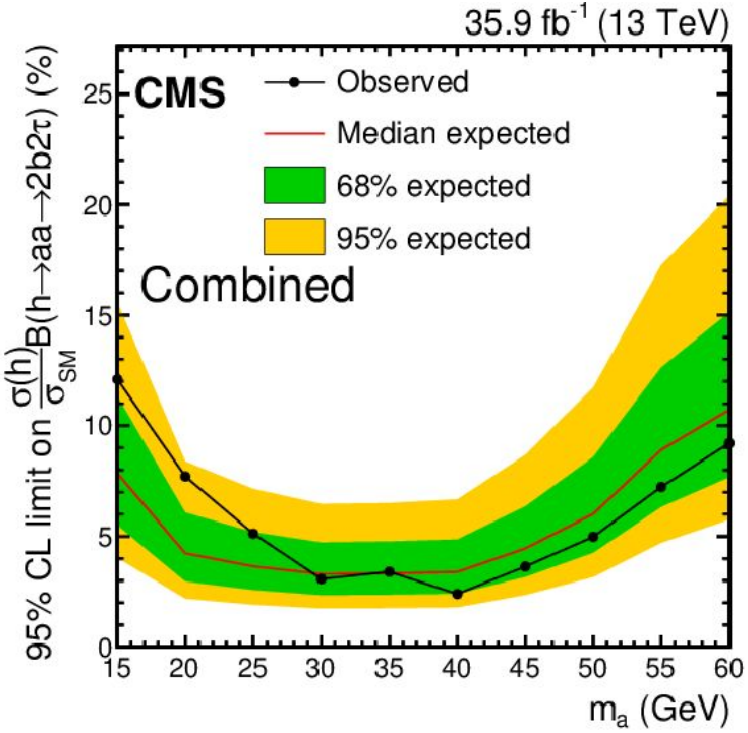
$H(125) \rightarrow aa \rightarrow bb\tau\tau$

arXiv:1805.10191

- No significant excess over SM prediction is observed
- Combined limits vary from 3% to 12% depending on m_a





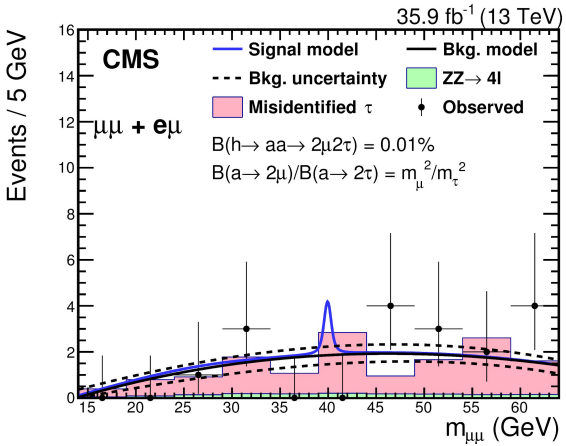


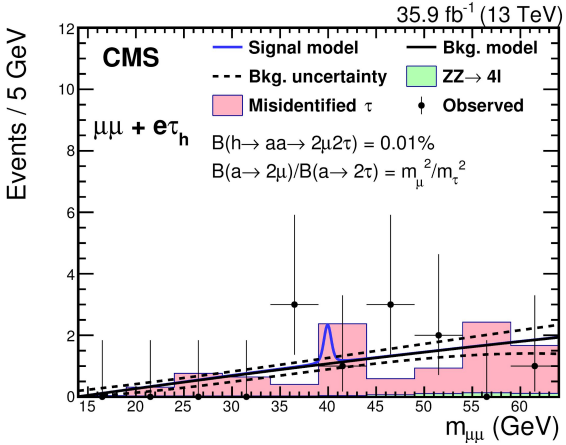
$H(125) \rightarrow aa \rightarrow \mu\mu\tau\tau$

arXiv:1805.04865

Analysis Overview

- Four different final states considered:
  $\mu\mu$+eμ, $\mu\mu$+eτ_h, $\mu\mu$+$\mu\tau_h$, $\mu\mu$+$\tau_h\tau_h$,
  - Events from $H \rightarrow aa \rightarrow 4\tau$ are considered in the signal
- Dominant backgrounds from events with jet$\rightarrow\tau_h$ mis-ID
  - Z+jets, WZ+jets, ZZ*$\rightarrow 2\ell 2q$, ttbar, QCD multijets
- Signal extracted w/ unbinned ML fit to $M^{vis}(\mu\mu)$ to probe m_a= [15.0, 62.5] GeV



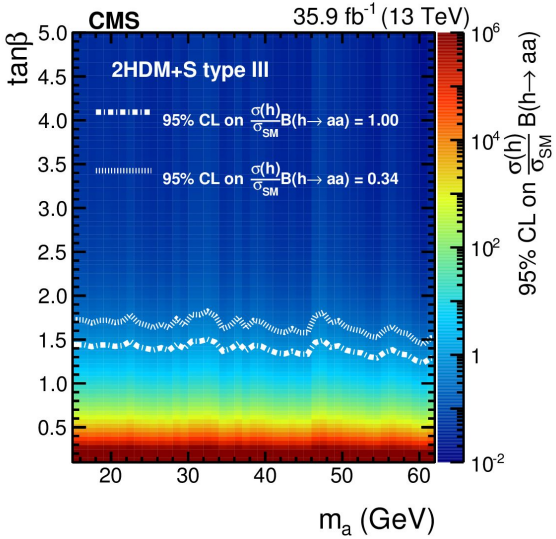


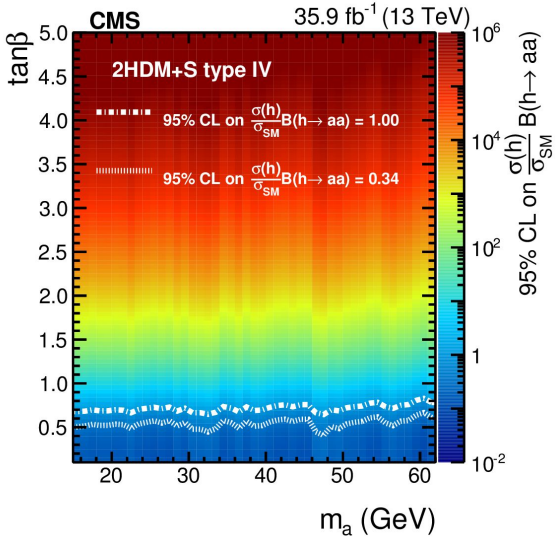
$H(125) \rightarrow aa \rightarrow \mu\mu\tau\tau$

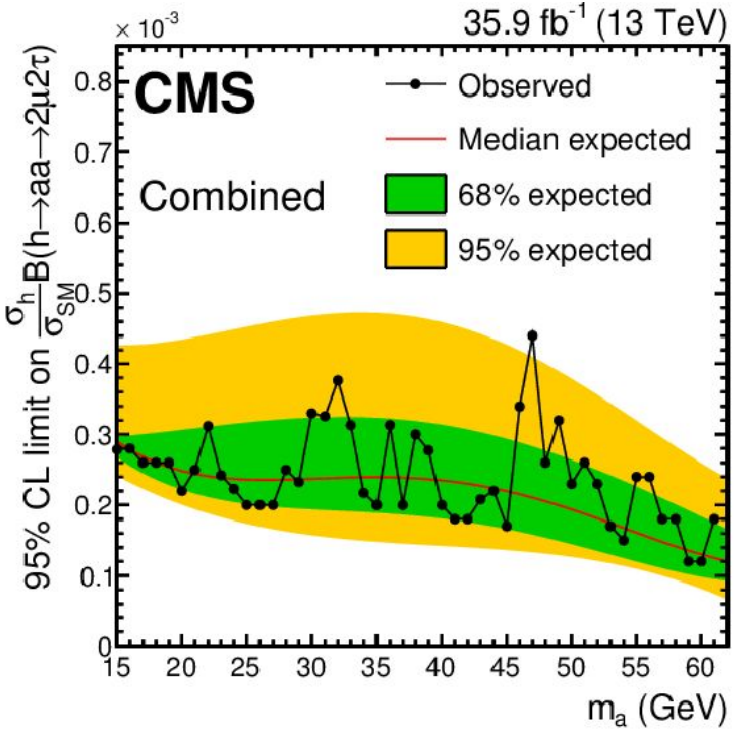
arXiv:1805.04865

- No significant excess over SM prediction is observed
- Combined limit for m_a = 60 GeV:

  $\sigma \times BR(H \rightarrow aa \rightarrow \mu\mu\tau\tau) = 1.2 \times 10^{-4} \times \sigma_{SM}$





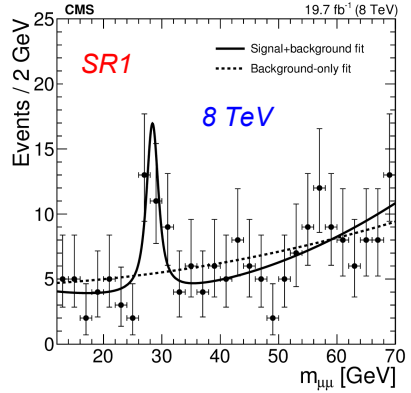


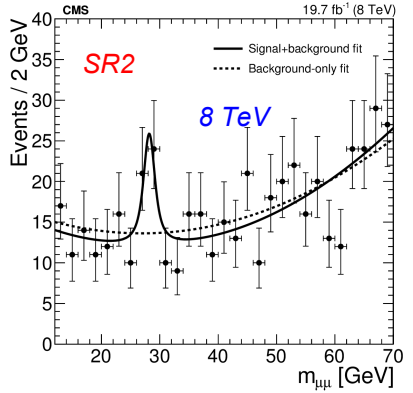
μμ Resonances in μμ+bj

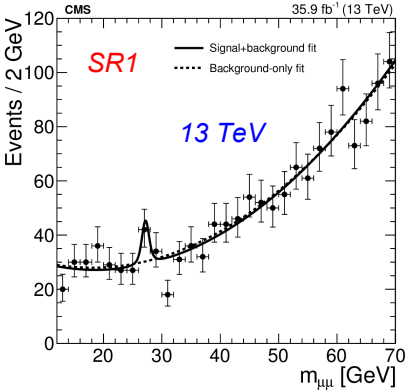
arXiv:1808.01890

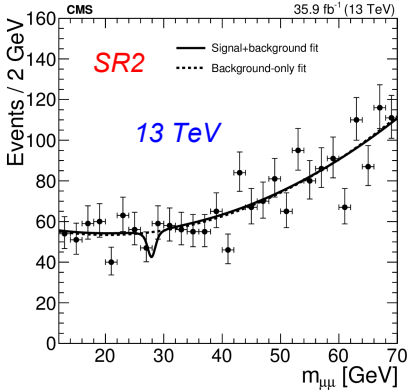
Analysis Overview

- Search for μμ resonances in range $m(\mu\mu) \in [12, 70]$ GeV
- Two signal regions defined:
  - SR1: μμ + a central *b*-jet + at least one forward jet
  - SR2: μμ + 2 central jets (≥ 1 *b*-tag) and no forward jets + E_T^{miss}









An excess (4.2σ in SR1, 2.9σ in SR2) of events is seen at 28 GeV in 8 TeV data ⟹ Not confirmed in 13 TeV data analyzed thus far (36 fb^{-1})

NEW $\tau\tau$ Resonances in $\tau\tau$+bj NEW

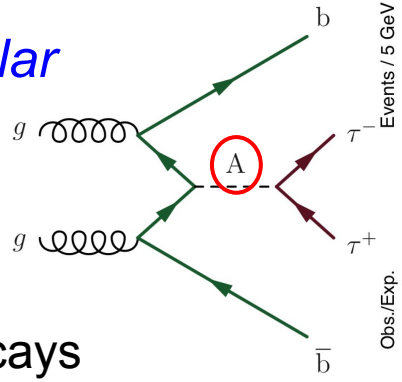
CMS-PAS-HIG-17-01

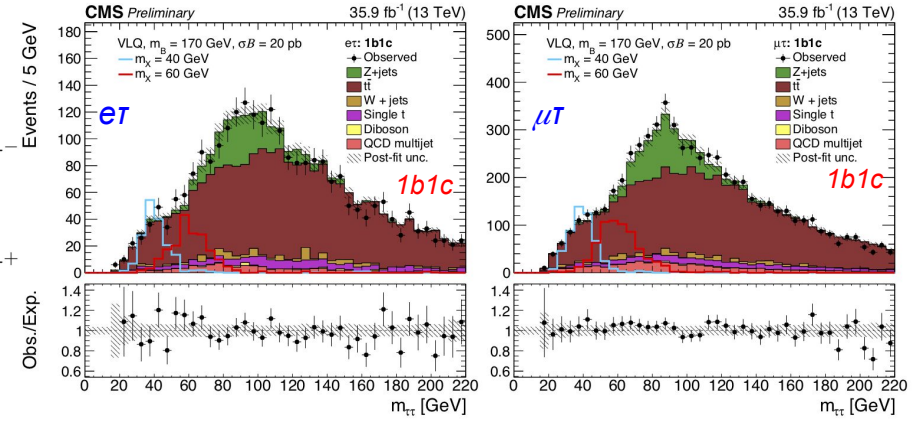
Signature: 2τ + at least 1 *b*-jet (b) + an additional jet, which can be central (c) or forward (f)

- $\tau\tau$ categorized by eτ_h, $\mu\tau_h$

Search for light pseudoscalar Higgs boson A($\tau\tau$)

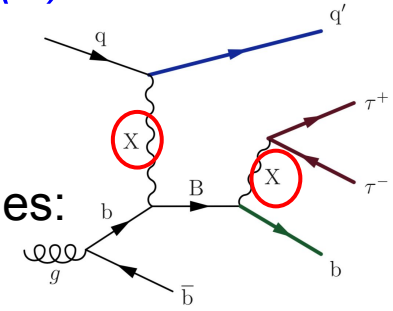
- m_T < 40 GeV to suppress ttbar production
- p_T^{miss} consistent with τ decays

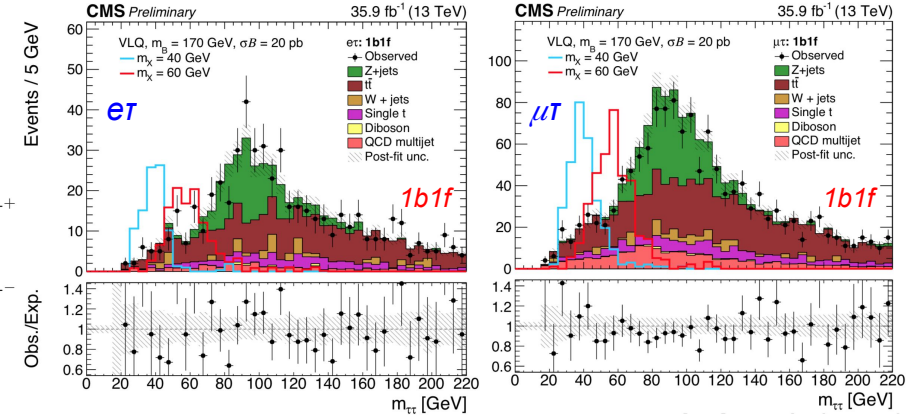




Search for X($\tau\tau$) produced via decay of vector-like quark (B)

- m_T < 60 GeV to suppress ttbar production
- 2 event jet-based categories:
  - 1b1c, 1b1f

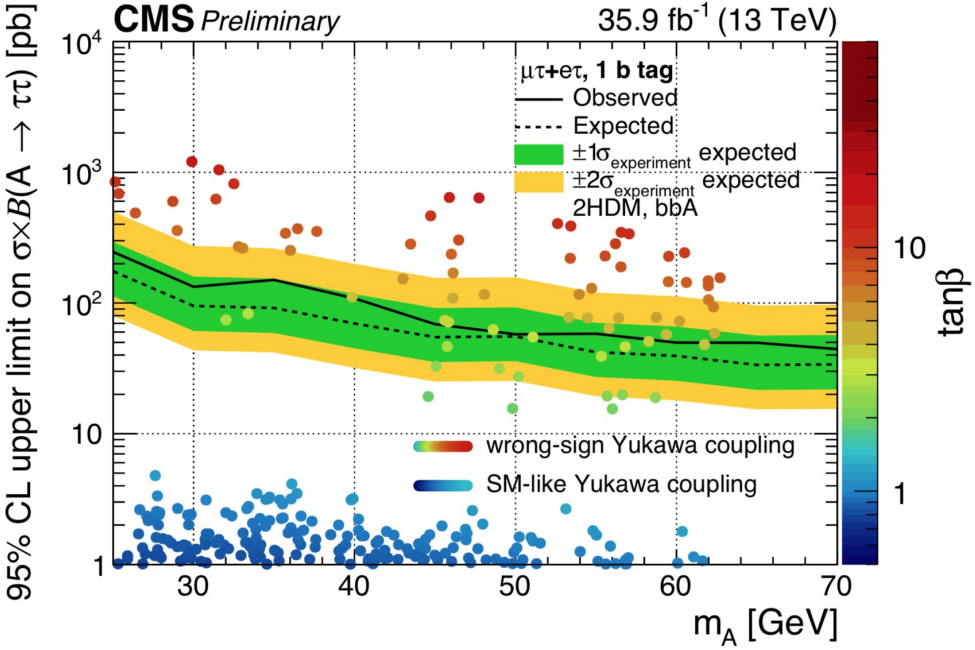


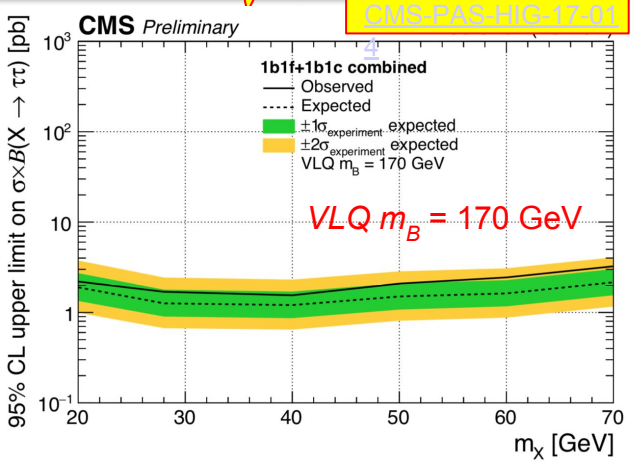


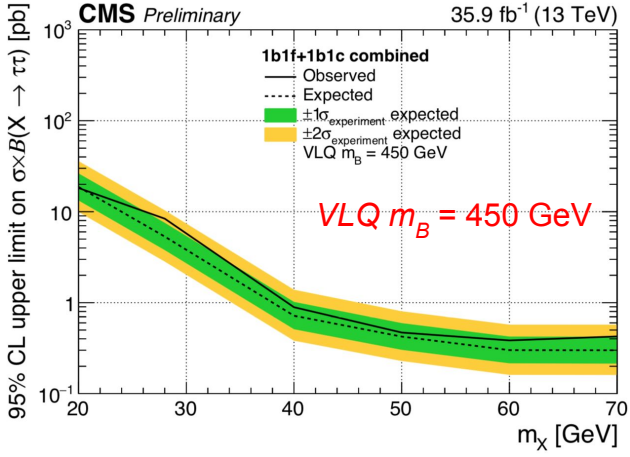
NEW ττ Resonances in ττ+bj NEW

CMS-PAS-HIG-17-01

- No significant excess over SM prediction is observed in $bbA(\tau\tau)$ or $X(\tau\tau)bj$ searches
- Limits set on $\sigma\times BR(A/X\rightarrow\tau\tau)$ vs m_A and m_X







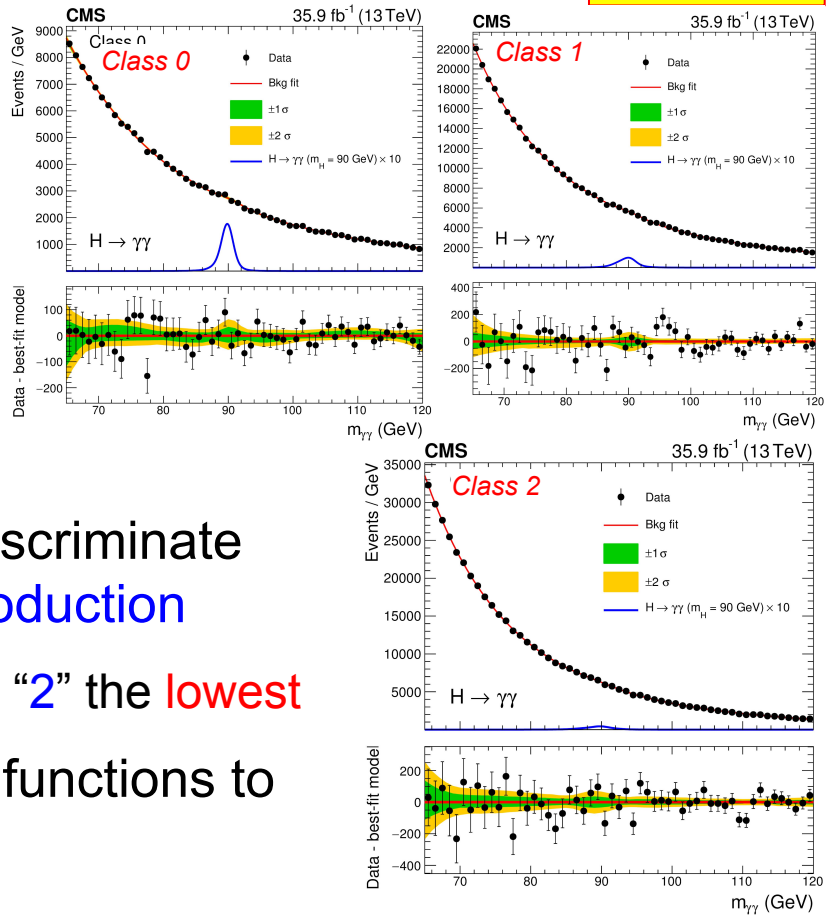
Low mass $X \to \gamma\gamma$

arXiv:1811.08459

Search for $X \to \gamma\gamma$: m_X= [65,120] GeV

Analysis Overview

- Trigger on di-photons with luminosity-dependent thresholds
- Require two isolated photons that pass a BDT-based identifier
- A multivariate event classifier is used to discriminate resonant (X) from continuum di-photon production
  - "Class 0" has highest expected sensitivity, "2" the lowest
- Background is modelled by fitting analytic functions to the observed diphoton mass distributions

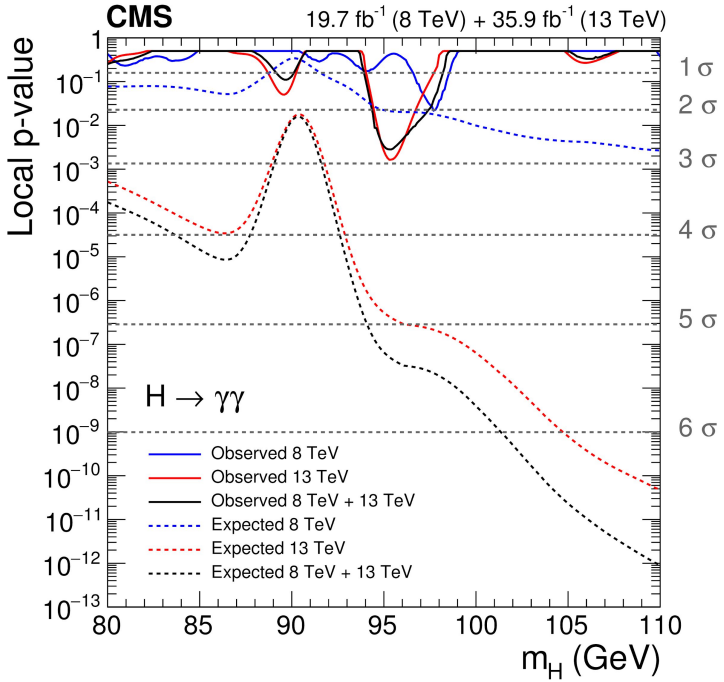


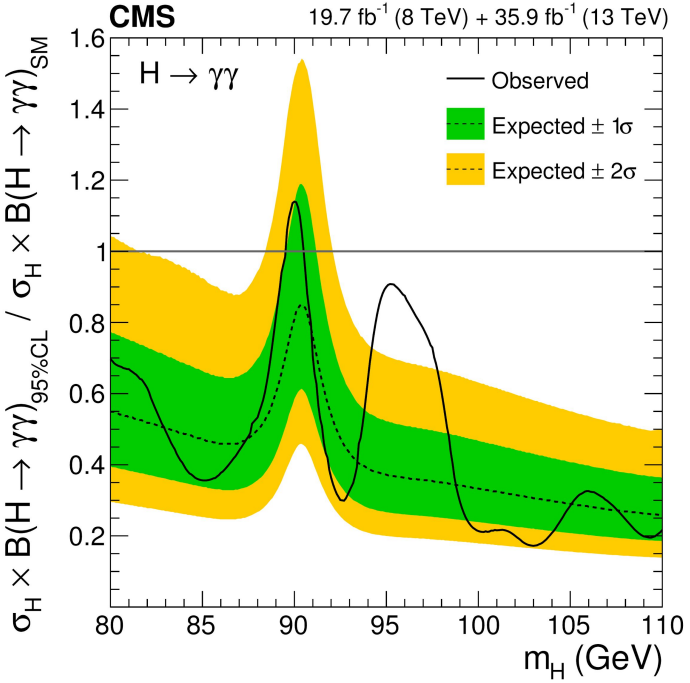
Low mass $X \rightarrow \gamma\gamma$

arXiv:1811.08459

No significant (>3σ) excess over SM prediction is observed [9]

- Combined 8+13 TeV results show an excess at ~95 GeV at the level of 2.8σ local (1.3σ global) significance



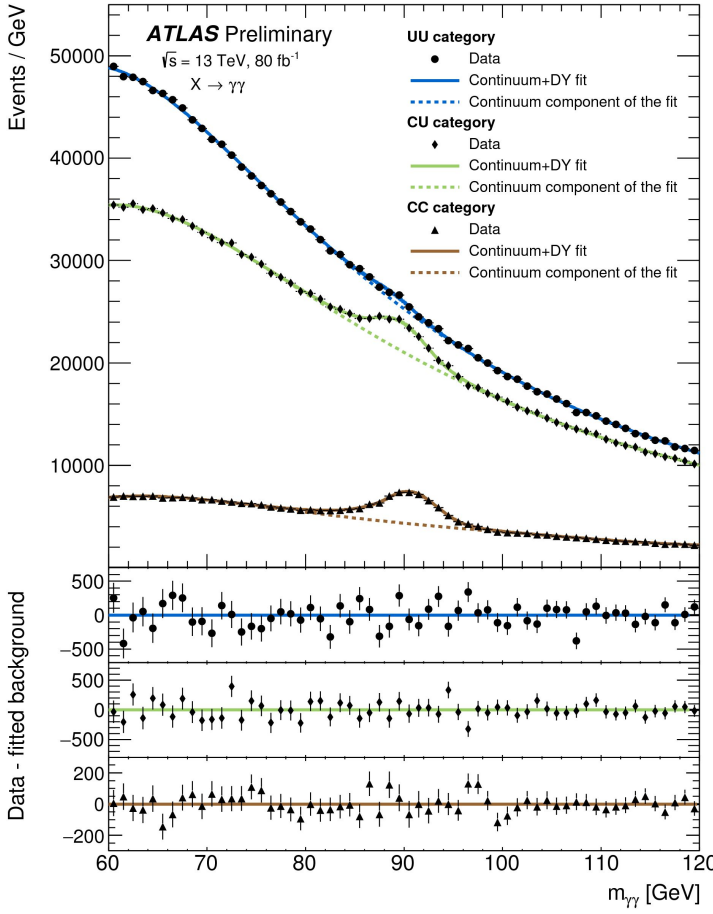


Low mass $X \to \gamma\gamma$

Search for $X \to \gamma\gamma$: m_X= [65,110] GeV

Analysis Overview

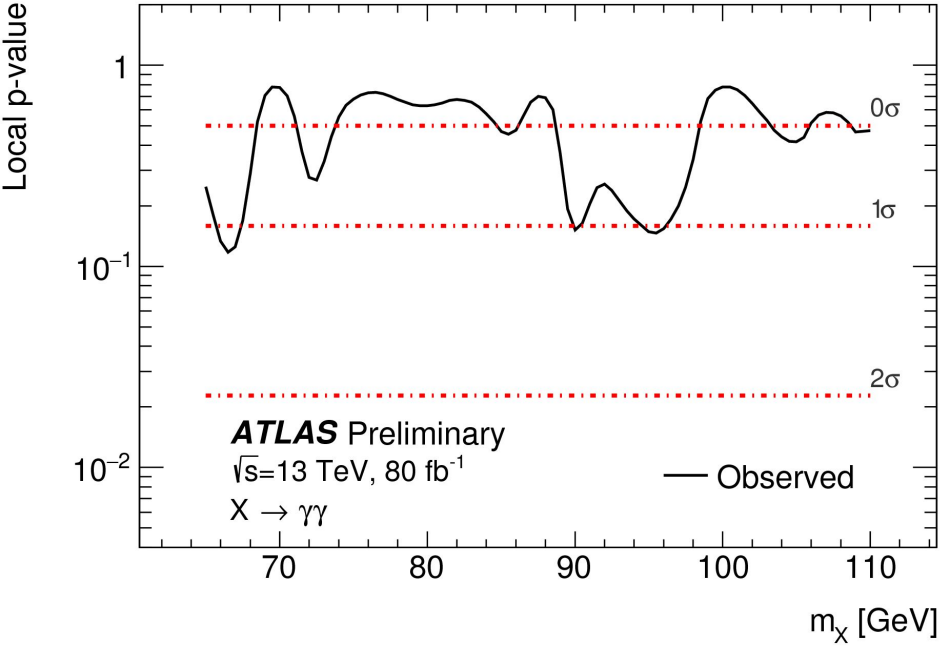
- Trigger on di-photons with luminosity-dependent thresholds
- Require two well-identified, isolated photons
  - Split in categories for photon conversions (CC, UC, UU): CC has more DY background
- Main backgrounds: SM $\gamma\gamma$/jγ/jj, Z boson (e$\to\gamma$ fakes)
  - Model non-resonant (continuum) and resonant DY backgrounds using data-driven approaches

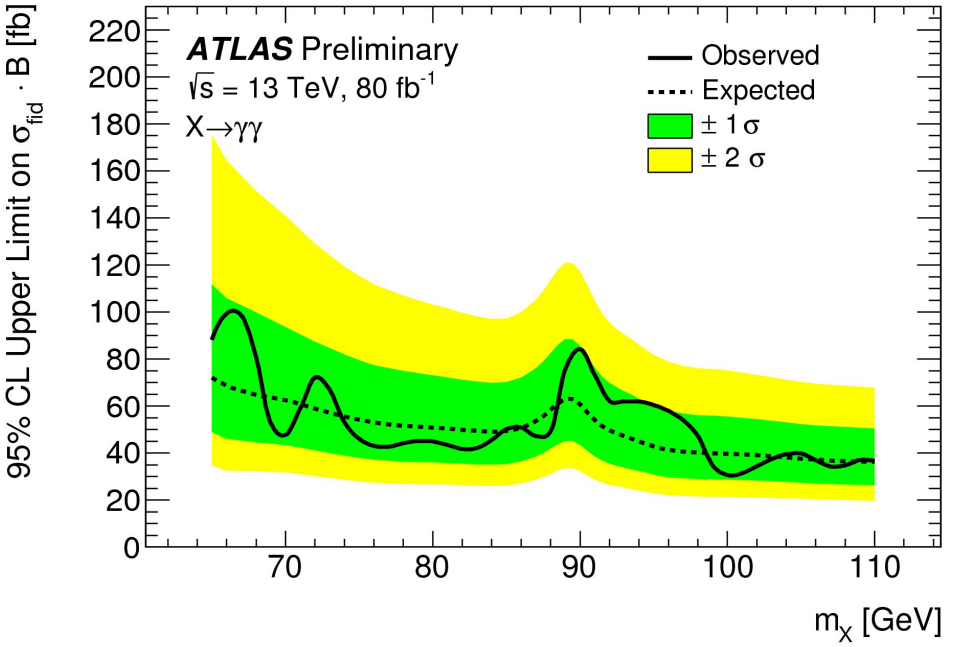


Low mass $X \to \gamma\gamma$

ATLAS-CONF-2016-025

- No evidence for significant excess beyond the SM using a narrow-width approximation to interpret the data





Conclusions and Outlook

ATLAS and CMS performed many searches for exotic decays of the 125 GeV Higgs boson and new low-mass particles decaying to photons and leptons

⇒ *Presented in this talk*:

$H(125) \to aa \to bbbb$ (ATLAS)
$H(125) \to aa \to \gamma\gamma jj$ (ATLAS)
$H(125) \to aa/Z_{(d)}Z_d \to \ell\ell\ell\ell$ (ATLAS)

$H(125) \to aa \to bb\mu\mu$ (ATLAS, CMS)
$H(125) \to aa \to bb\tau\tau$ (CMS)
$H(125) \to aa \to \mu\mu\tau\tau$ (CMS)

$\mu\mu$ Resonances in $\mu\mu$+bj (CMS)
$\tau\tau$ Resonances in $\tau\tau$+bj (CMS)
Low mass $X \to \gamma\gamma$ (ATLAS, CMS)

No statistically significant excess is observed in any of these searches

⇒ Limits are set on cross section × branching fraction and interpreted in the context of BSM models such as the 2HDM+*S*

Proton-proton collisions recently ended with ~160 fb^{-1} delivered to each of ATLAS and CMS, so more data is in hand to be analyzed for many searches

⇒ **Stay tuned for more results from Run-II of the LHC**

Bonus Material

$H(125) \rightarrow aa \rightarrow bb\mu\mu$

NEW NEW

CMS-PAS-HIG-18-01

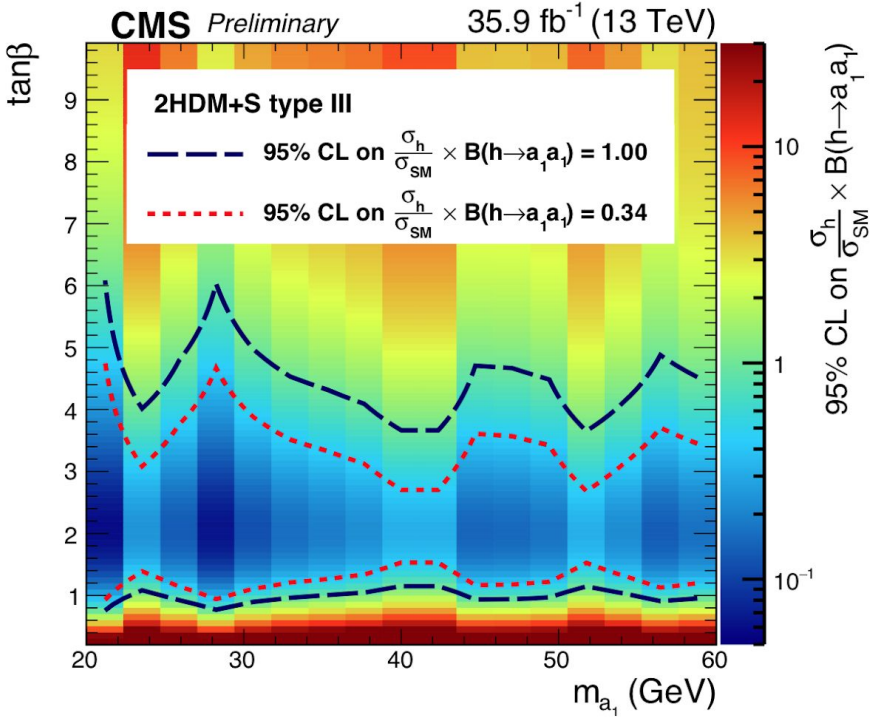


Figure 6: Observed upper limits on $\mathcal{B}(\mathrm{h} \rightarrow \mathrm{a_1 a_1})$ in the plane of $(m_{\mathrm{a_1}}, \tan\beta)$ for type-III 2HDM+S, including $\mu^+\mu^-\tau^+\tau^-$ signal that is misidentified as $\mu^+\mu^-\mathrm{b\bar{b}}$.