Additional neutral light Higgs bosons at ATLAS and CMS

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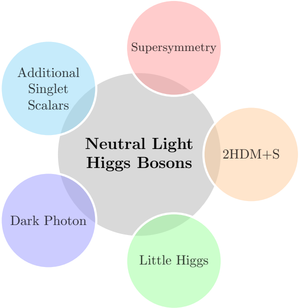
On behalf of the ATLAS and CMS collaborations

After 8 years of the discovery: is the nature of the Higgs boson completely determined?

Extended Scalar Sectors

- possibility of light states in several well-motivated models
  - light bosons (**a**) can couple to the 125-GeV Higgs boson (**h**)



The 2HDM+S Phys.Rev.D 90 (2014) 7, 075004

- 2HDM near decoupling limit: $\alpha \to \beta - \pi/2$
- add one complex scalar singlet: $S = \frac{1}{\sqrt{2}}(S_R + iS_I)$
- potential light boson: $a = \cos\theta_a S_I + \sin\theta_a A \quad (\theta_a \ll 1)$
  - couplings to fermions: $\xi_a \sim \sin\theta_a \cdot \xi_A$

Coupling	**Type-I**	**Type-II**	**Type-III**	**Type-IV**
ξ_A^u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
ξ_A^d	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
ξ_A^l	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

Probing Models with Light Bosons

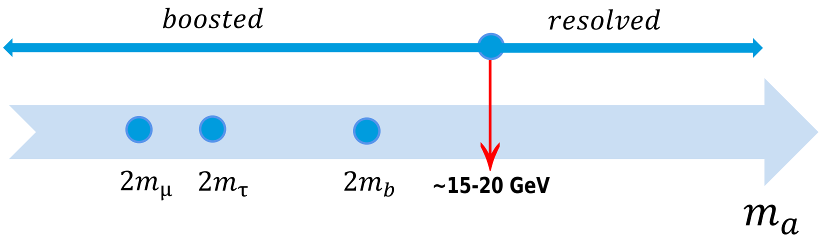
× direct searches in production mode? ⇒ limited by small couplings of **a** to fermions

× indirect constraints from h cuplings? ⇒ $\mathcal{B}(h \to \text{BSM})$ still relatively large

✓ alternative: *search for light bosons through exotic decays of h*

Exotic Decay Topologies: $h \to aa(Za) \to X\bar{X}Y\bar{Y}$

- ▷ large variety of models and scenarios with rich phenomenology
  - ✓ multiple searches in distinct final states required to effectively probe the parameter space
  - ✓ ATLAS and CMS have designed an extensive program to cover multiple decay channels
- ▷ various strategies for experimental analyses
  - ✓ for $m_a \ll m_h$, the light bosons become highly boosted
  - ✓ two regimes are normally distinguished: *Resolved vs. Boosted*
    - boosted regime normally requires dedicated analysis techniques



Run II Analyses

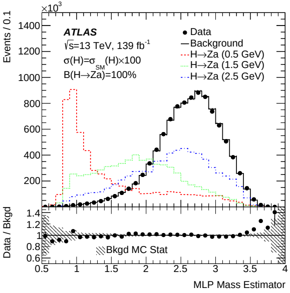
- **ATLAS**
  - **Boosted**
    - $h \to Za \to lljj$ — accepted by PRL
    - $h \to aa \to bbbb$ — accepted by PRD
  - **Resolved**
    - $h \to aa \to \gamma\gamma jj$ — Phys.Lett.B 782 (2018) 750-767
    - $h \to aa \to \mu\mu bb$ — Phys.Lett.B 790 (2019) 1-21
    - $h \to aa \to bbbb$ — JHEP 10 (2018) 031
  - $h \to aa(Za) \to llll \; (l \equiv e \; or \; \mu)$ — JHEP 06 (2018) 166
- **CMS**
  - **Boosted**
    - $h \to aa \to \mu\mu\mu\mu$ — Phys.Lett.B 796 (2019) 131-154
    - $h \to aa \to \mu\mu\tau\tau$ — JHEP 08 (2020) 139
    - $h \to aa \to \tau\tau\tau\tau$ — Phys.Lett.B 800 (2020) 135087
  - **Resolved**
    - $h \to aa \to \mu\mu\tau\tau$ — JHEP 11 (2018) 018
    - $h \to aa \to \mu\mu bb$ — Phys.Lett.B 795 (2019) 398-423
    - $h \to aa \to \tau\tau bb$ — Phys.Lett.B 785 (2018) 462
  - $h \to aa(Za) \to llll \; (l \equiv e \; or \; \mu)$ — CMS-PAS-HIG-19-007

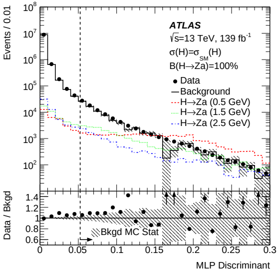
$h \to Za \to lljj$

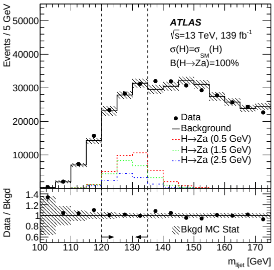
accepted by PRL

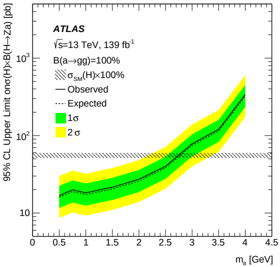
ATLAS (boosted)

- ✓ mass range: $0.5 < m_a < 4$ GeV
- ✓ h production mechanisms: ggH
- ✓ neural network (MLP) employed to discriminate between boosted di-jet (signal) and single-jet (background)
- ✓ signal extraction: counting experiment in signal region
- ✓ background estimation: Z+Jets dominates, modeled with a combination of simulation and data







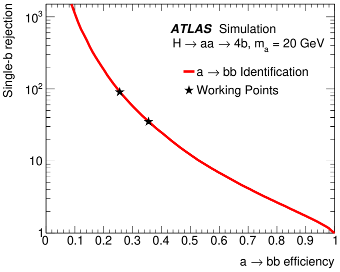


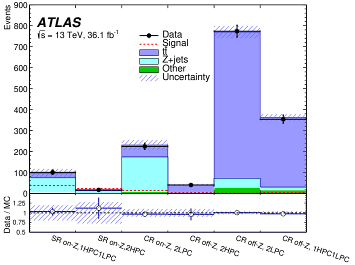
$h \to aa \to bbbb$ (‡)

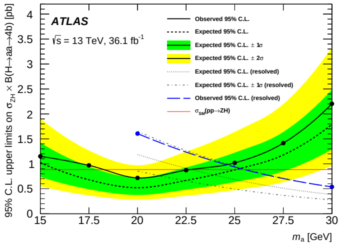
accepted by PRD

ATLAS (boosted)

- ✓ mass range: $15 < m_a < 30$ GeV
- ✓ h production mechanisms: ZH
- ✓ MVA (BDT) tagger developed to discriminate between boosted di-b jet (signal) and single-b jet (background)
- ✓ signal extraction: fit to binned distribution formed by 2 SR and 4 CR (regions defined according to two BDT working points and Z-mass window)
- ✓ background estimation: Z+Jets and $t\bar{t}$ dominate, modeled using various CRs in data







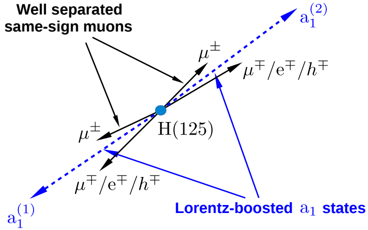
‡ complements previous search ($20 < m_a < 60$ GeV) in same final state: JHEP 10 (2018) 031

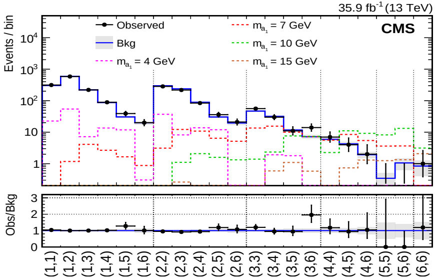
$h \to aa \to \tau\tau\tau\tau$

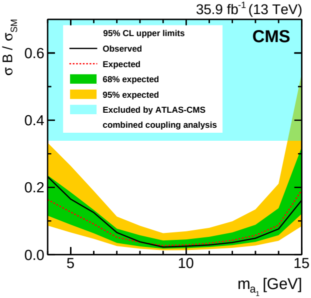
Phys.Lett.B 800 (2020) 135087

CMS (boosted)

- ✓ mass range: $4 < m_a < 15$ GeV
- ✓ h production mechanisms: ggH (main), VBF, VH, and ttH
- ✓ $h \to aa \to \mu\mu\tau\tau$ contribution included
- ✓ signal extraction: fit to binned 2D $m_1(\mu, trk)$ *vs.* $m_2(\mu, trk)$ distribution
- ✓ background estimation: QCD-multijet dominates, modeled using several CRs in data





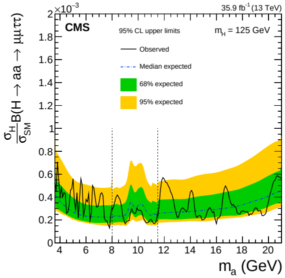


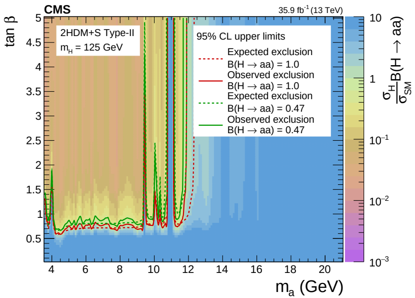
$h \to aa \to \mu\mu\tau\tau$

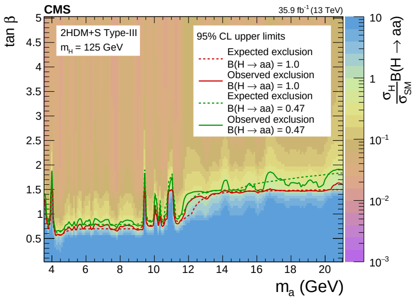
JHEP 08 (2020) 139

CMS (boosted)

- ✓ mass range: $3.6 < m_a < 21$ GeV
- ✓ h, $H(300)$ production mechanisms: ggH (main) and VBF
- ✓ special reconstruction technique to efficiently identify $a \to \tau_\mu \tau_h$
- ✓ signal extraction: fit to unbinned 2D $m(\mu,\mu)$ $vs.$ $m(\mu,\mu,\tau_\mu,\tau_h)$ distribution
- ✓ background estimation: Z+Jets and QCD-multijet dominate, modeled using CR in data







Coupling	ξ_A^u	ξ_A^d	ξ_A^l
Type-II	$\cot\beta$	$\tan\beta$	$\tan\beta$

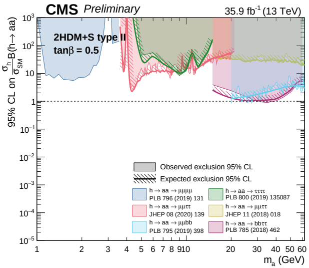
ATL-PHYS-PUB-2018-045

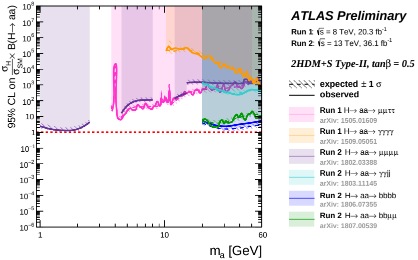
CMS-HIG-Summary-Results

CMS

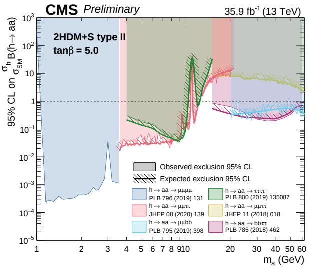
ATLAS

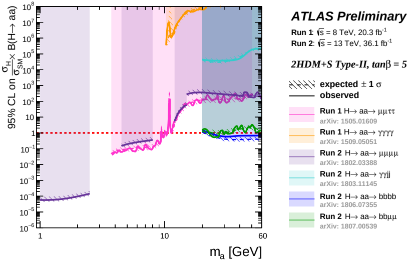
$\tan\beta = \mathbf{0.5}$





$\tan\beta = \mathbf{5}$





Coupling	ξ_A^u	ξ_A^d	ξ_A^l
Type-III	$\cot\beta$	$-\cot\beta$	$\tan\beta$

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CMS-HIG-Summary-Results

CMS

ATLAS

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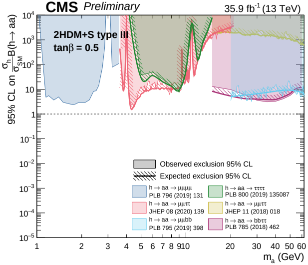
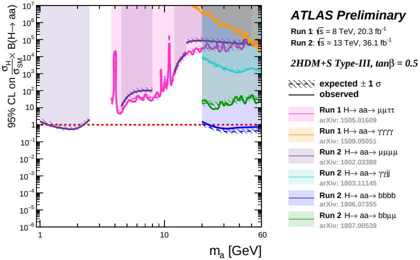
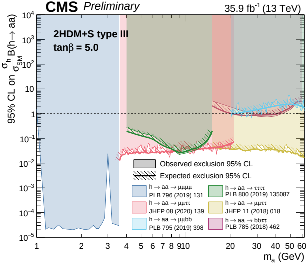
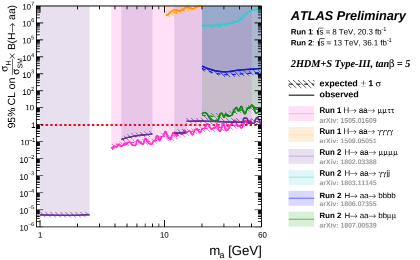




$\tan\beta = \mathbf{5}$





Summary

- ATLAS and CMS immersed in a broad program of searches for light bosons
  - ✓ no sign of additional neutral light Higgs bosons yet
  - ✓ analyses span a wide mass range of the light states
    - use of sophisticated analysis techniques to deal with boosted topologies
  - ✓ new promising decay channels being exploited
  - ✓ more interesting results to come with the full Run 2 dataset
- vast parameter phase-space still to be probed in many well-motivated models
  - ✓ inclusion of unexplored and challenging final states might help excluding it

Summary

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Thanks for your attention!

Backup

The 2HDM+S

Two Simple Assumptions ...

- 2HDM is near or in the decoupling limit (h becomes very SM-like): $\alpha \to \beta - \pi/2$
- Add one complex scalar singlet $S = \frac{1}{\sqrt{2}}(S_R + iS_I)$:

$$V_{2HDM+S}(H_1, H_2, S) = V_{2HDM}(H_1, H_2) + \lambda S H_1 H_2 + \frac{\kappa}{3} S^3 + \cdots$$

Light Boson Couplings

✓ a (the mostly-singlet-like pseudoscalar)

$$a = \cos\theta_a S_I + \sin\theta_a A \qquad (\theta_a \ll 1)$$

✓ could potentially be a light boson $\Rightarrow$ h exotic decays

$$h \to aa \to X\bar{X}Y\bar{Y}(m_a < m_h/2) \;\mid\; h \to aZ \to X\bar{X}Y\bar{Y}(m_a < m_h - m_Z)$$

✓ with couplings to fermions driven by: $\xi_a \sim \sin\theta_a \cdot \xi_A$

Eigenstate	**Coupling**	**Type-I**	**Type-II**	**Type-III**	**Type-IV**
	ξ_A^u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
A	ξ_A^d	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
	ξ_A^l	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

Coupling	ξ_A^u	ξ_A^d	ξ_A^l
Type-I	$\cot\beta$	$-\cot\beta$	$-\cot\beta$

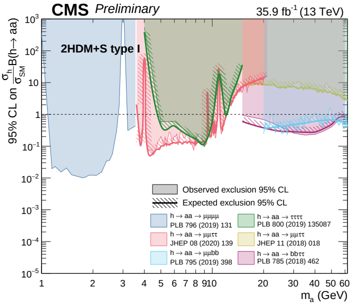
ATL-PHYS-PUB-2018-045

CMS-HIG-Summary-Results

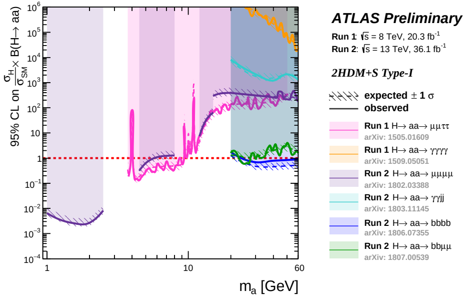
•

$B(a \to X\bar{X})$ are independent of $\tan\beta$ for this model type

CMS



ATLAS



Coupling	ξ_A^u	ξ_A^d	ξ_A^l
Type-IV	$\cot\beta$	$\tan\beta$	$-\cot\beta$

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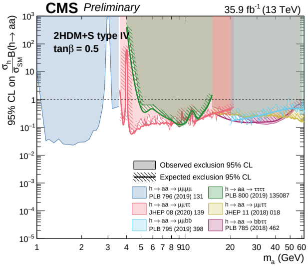
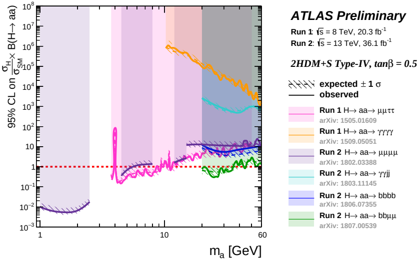
CMS-HIG-Summary-Results

CMS

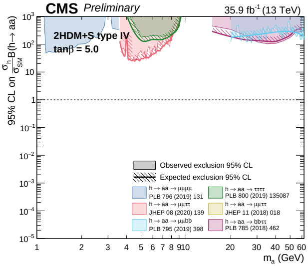
ATLAS

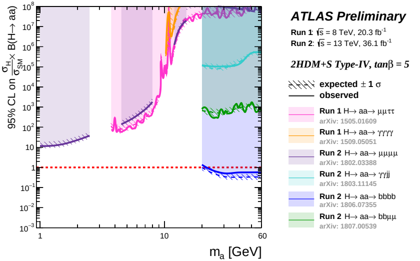
$\tan\beta = 0.5$





$\tan\beta = 5$





Outlook on ATLAS and CMS efforts within 2HDM+S

Model	**Region**	**Status**	**Potential Channels*** $(a \to X\bar{X})$
Type-I	-	○ (green)	-
Type-II	$\tan\beta < 1$	○ (yellow)	up-type quarks and gluons (e.g.: $a \to c\bar{c}$)
	$\tan\beta > 1$	○ (green)	-
Type-III	$\tan\beta < 1$	○ (yellow)	quarks and gluons (e.g.: $a \to c\bar{c}, s\bar{s}$)
	$\tan\beta > 1$	○ (green)	-
Type-IV	$\tan\beta < 1$	○ (green)	-
	$\tan\beta > 1$	○ (yellow)	down-type quarks and gluons (e.g.: $a \to s\bar{s}$)

○ (green) : moderately constrained by current analyses in the entire mass range

○ (yellow) : weakly constrained by current analyses for very light bosons ($m_a \lesssim 15$ GeV)

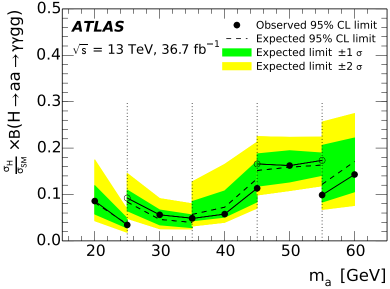
*only if not ○ (green), final states that might help improve current limits

$h \to aa \to \gamma\gamma jj$

Phys.Lett.B 782 (2018) 750-767

ATLAS (resolved)

- ✓ mass range: $20 < m_a < 60$ GeV
- ✓ h production mechanisms: ggH and VBF (main)
- ✓ five overlapping $m(\gamma,\gamma)$ regions are defined
- ✓ signal extraction: binned fit to SR and CRs (4 bins)
- ✓ background estimation: QCD multijet dominates, modeled with data-driven ABCD method



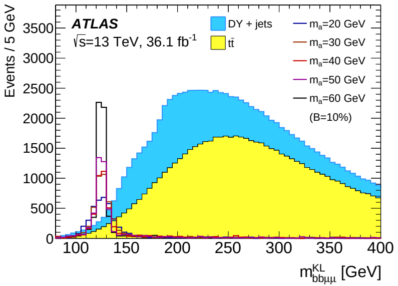
$m_{\gamma\gamma}$ regime	Definition	Range of m_a values	x_{R} [GeV]
1	$17.5\ \mathrm{GeV} < m_{\gamma\gamma} < 27.5\ \mathrm{GeV}$	$20\ \mathrm{GeV} \leq m_a \leq 25\ \mathrm{GeV}$	12
2	$22.5\ \mathrm{GeV} < m_{\gamma\gamma} < 37.5\ \mathrm{GeV}$	$25\ \mathrm{GeV} \leq m_a \leq 35\ \mathrm{GeV}$	12
3	$32.5\ \mathrm{GeV} < m_{\gamma\gamma} < 47.5\ \mathrm{GeV}$	$35\ \mathrm{GeV} \leq m_a \leq 45\ \mathrm{GeV}$	16
4	$42.5\ \mathrm{GeV} < m_{\gamma\gamma} < 57.5\ \mathrm{GeV}$	$45\ \mathrm{GeV} \leq m_a \leq 55\ \mathrm{GeV}$	20
5	$52.5\ \mathrm{GeV} < m_{\gamma\gamma} < 65.0\ \mathrm{GeV}$	$55\ \mathrm{GeV} \leq m_a \leq 60\ \mathrm{GeV}$	24

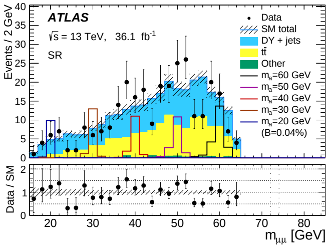
$h \to aa \to bb\mu\mu$

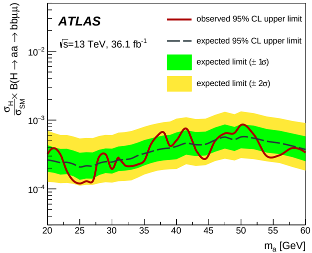
Phys.Lett.B 790 (2019) 1-21

ATLAS (resolved)

- ✓ mass range: $20 < m_a < 60$ GeV
- ✓ h production mechanisms: ggH and VBF
- ✓ a kinematic fit ($m(\mu, \mu) \simeq m(b, b)$) is employed to improve the resolution of $m(\mu, \mu, b, b)$
- ✓ signal extraction: binned fit to the $m(\mu, \mu)$ distribution
- ✓ background estimation: Z+Jets and $t\bar{t}$ dominate, modeled with a combination of simulation and data





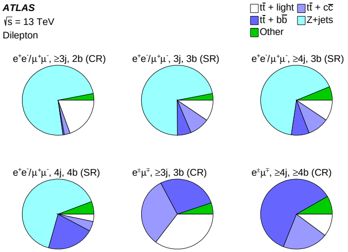


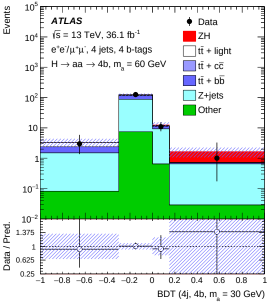
$h \to aa \to bbbb$

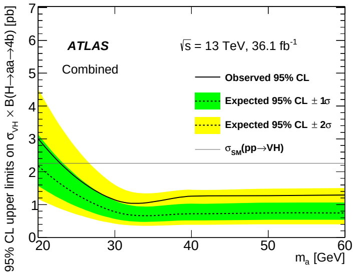
JHEP 10 (2018) 031

ATLAS (resolved)

- ✓ mass range: $20 < m_a < 60$ GeV
- ✓ h production mechanisms: VH
- ✓ several categories are defined for both single- and di-lepton channels
- ✓ signal extraction: binned fit to BDT distribution for each category
- ✓ background estimation: Z+Jets and $t\bar{t}$ dominate, modeled with a combination of simulation and data





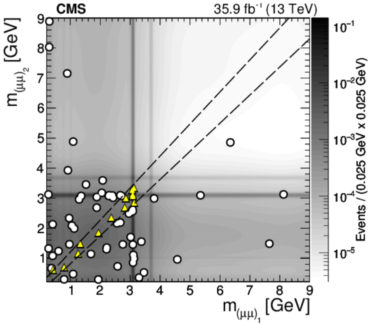


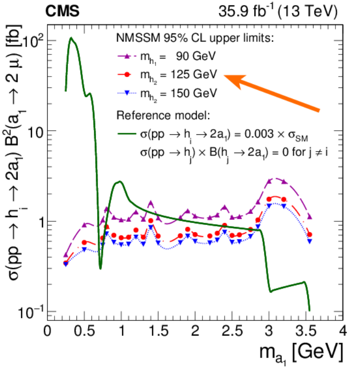
$h \to aa \to \mu\mu\mu\mu$

Phys.Lett.B 796 (2019) 131-154

CMS (boosted)

- ✓ mass range: $0.25 < m_a < 3.55$ GeV
- ✓ h production mechanisms: ggH
- ✓ events are selected if $m_1(\mu,\mu) \simeq m_2(\mu,\mu)$
- ✓ signal extraction: unbinned fit to the 2D $m_1(\mu,\mu)$ vs. $m_2(\mu,\mu)$ distribution
- ✓ background estimation: QCD multijet ($b\bar{b}$) dominates, modeled using CRs in data



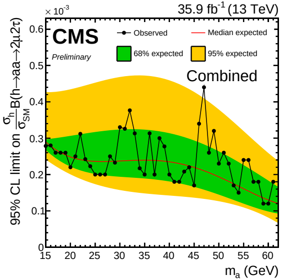


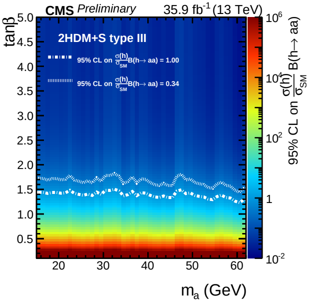
$h \to aa \to \mu\mu\tau\tau$

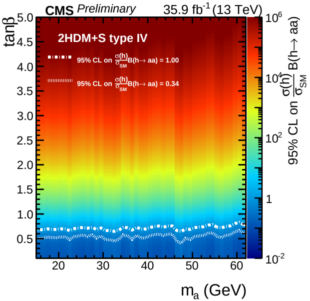
JHEP 1811 (2018) 018

CMS (resolved)

- ✓ mass range: $15.0 < m_a < 62.5$ GeV
- ✓ h production mechanisms: ggH and VBF
- ✓ $h \to aa \to \tau\tau\tau\tau$ contribution included
- ✓ signal extraction: unbinned fit to the $m(\mu, \mu)$ distribution
- ✓ background estimation: Z+Jets and WZ+Jets dominate, modeled using CRs in data







$h \to aa \to bb\tau\tau$

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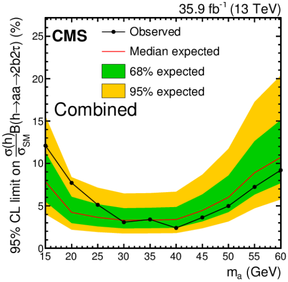
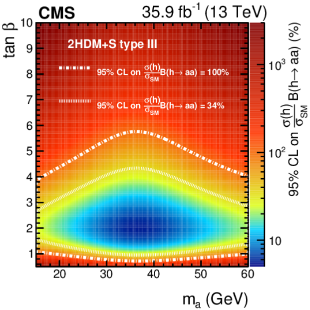
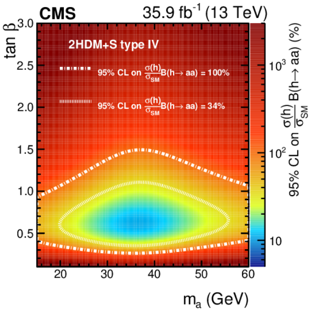
CMS (resolved)

- ✓ mass range: $15.0 < m_a < 60$ GeV
- ✓ h production mechanisms: ggH, VBF and VH
- ✓ three different $\tau\tau$ decay channels: $e\mu$, $e\tau_h$ and $\mu\tau_h$
- ✓ signal extraction: binned fit to the $m_{vis}(\tau, \tau)$ distribution
- ✓ background estimation: $t\bar{t}$, Z/W+Jets, and QCD multijet dominate, modeled using combination of simulation and data







$h \to aa \to bb\mu\mu$

Phys.Lett.B 795 (2019) 398-423

CMS (resolved)

- ✓ mass range: $20.0 < m_a < 62.5$ GeV
- ✓ h production mechanisms: ggH and VBF
- ✓ categorization (3 cats.) according to the b tagging discriminator for one jet
- ✓ signal extraction: unbinned fit to the $m(\mu, \mu)$ distribution
- ✓ background estimation: Z+Jets and $t\bar{t}$ dominate, modeled using CR in data