Searches for non-Standard Model decays of the Higgs to two light bosons in ATLAS and CMS

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on behalf of the ATLAS and CMS collaborations

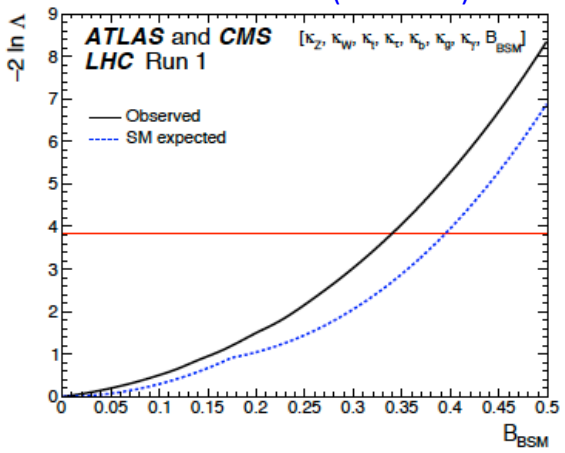
Exotic Higgs: motivation

- The observation of the 125 GeV Higgs has opened new perspectives to search for non-Standard Model or “exotic” decays of the Higgs boson.

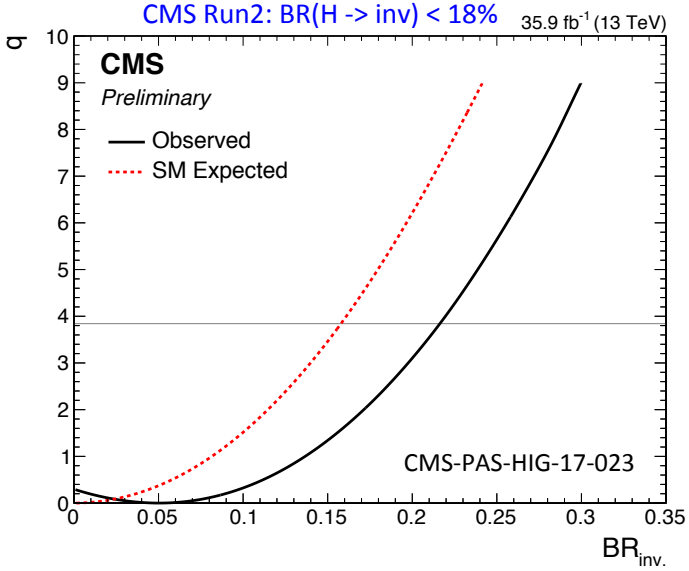
- Combination of Higgs couplings measurements of both CMS and ATLAS, allow non-SM decays of the Higgs boson.

- Exotic decays of H(125) boson are generic predictions of many well motivated theories of extended Higgs sectors (2HDM, NMSSM, Dark Matter models etc).

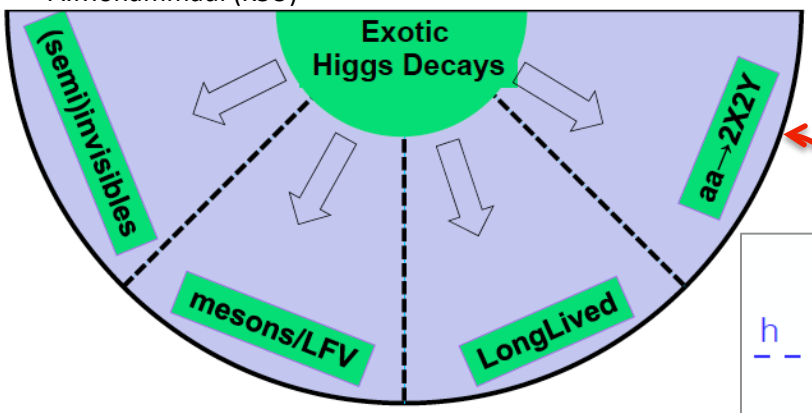
ATLAS+CMS Run1: BR(H -> BSM) < 34%



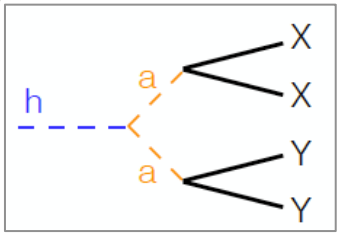
CMS Run2: BR(H -> inv) < 18%



A.Mohammadi (KSU)

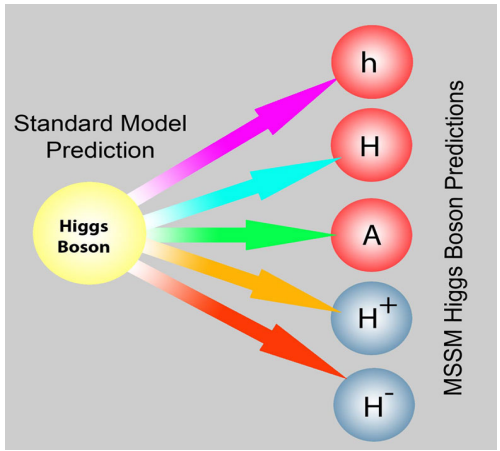


This talk



Extended Higgs sectors

- Simplest extensions of the SM: SM + s, 2HDM + s, composite models…
  - 2HDM / MSSM: 5 physical Higgs bosons: 2 scalars (h, H) + 1 pseudoscalar (A) + 2 charged Higgses ($H^{\pm}$)
  - NMSSM: 7 physical Higgs bosons: 3 scalars ($H_{1,2,3}$) + 2 pseudoscalars (A_1,A_2) + 2 charged Higgses ($H^{\pm}$)
  - Composite: h + excited states



Minimal extensions of the SM

Model	Particle content
SM	h, CP-even
2HDM/MSSM	h, H, CP-even A, CP-odd $H^{\pm}$
NMSSM	H_1, H_2, H_3 CP-even A_1, A_2 CP-odd $H^{\pm}$
Composite	h, CP-even + excited states

- 2HDM/NMSSM can allow a light enough pseudo-scalar A(a) which can yield a sizeable h → aa branching ratio.

h ⟶ aa phenomenology

https://arxiv.org/pdf/1312.4992v5.pdf

- 2HDM + s

	Type-1	Type-2	Type-3 (lepton-specific)	Type-4 (flipped)
Up-type quarks	Φ_2	Φ_2	Φ_2	Φ_2
Down-type quarks	Φ_2	Φ_1	Φ_2	Φ_1
Charged leptons	Φ_2	Φ_1	Φ_1	Φ_2

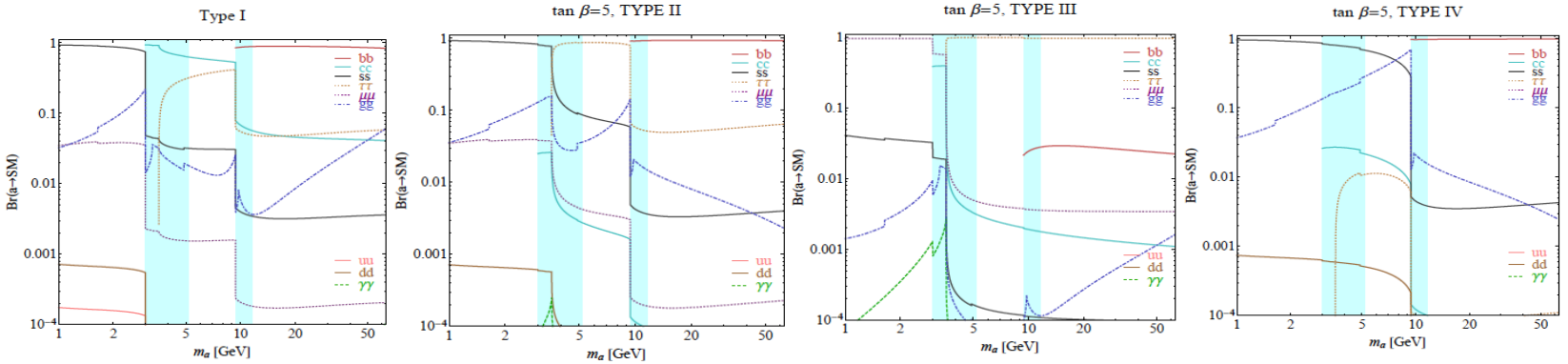
Yukawa couplings to the pseudo-scalar a boson normalized to SM Higgs Yukawa couplings

	Type-1	Type-2	Type-3 (lepton-specific)	Type-4 (flipped)
Up-type quarks	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
Down-type quarks	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
Charged leptons	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

$\tan\beta = v_2/v_1$

  - Type-1: no dependence on tanβ
  - Type-2 (NMSSM-like): couplings to leptons and down-type quarks enhanced at high tanβ.
  - Type-3 (lepton-specific): couplings to leptons are enhanced at high tanβ.
  - Type-4 (flipped): couplings to down-type quarks enhanced at high tanβ.

- h → aa → 2X2Y with X and Y could be any type of fermions, gluon or photon.
  - BR of a to SM particles depend on the mass of a, the model type and on tanβ.



h → aa searches overview

- Overview of Run1 [8 TeV] and Run2 [13 TeV] searches in ATLAS and CMS:

Final state	ATLAS			CMS		
	Dataset	ID	arXiv	Dataset	ID	arXiv
H→aa→4l (h→ZZ$_d$/Z$_d$Z$_d$→4l)	13 TeV	JHEP06(2018)166	1802.03388	8 TeV + 13 TeV	Phys. Lett. B 752 (2016) 146, HIG-18-003 (PAS)	1506.00424
H→aa→4τ	-	-	-	8 TeV	JHEP(2016)079	1510.06534 1701.02032
H→aa→2b2μ	13 TeV	Submitted to PLB	1807.00539	8 TeV	JHEP(2017)076	1701.02032
H→aa→2μ2τ	8 TeV	Phys. Rev. D92 (2015) 052002	1505.01609	8 TeV + 13 TeV	Submitted to JHEP	1701.02032 1805.04865
H→aa→2b2τ	-	-	-	13 TeV	Submitted to PLB	1805.10191
H→aa→4b	13 TeV	Submitted to JHEP	1806.07355	-	-	-
H→aa→4γ	8 TeV	EPJC 76(4) 2016	1509.05051	-	-	-
H→aa→2γ2g	13 TeV	Phys. Lett. B 782 (2018) 750	1803.11145	-	-	-

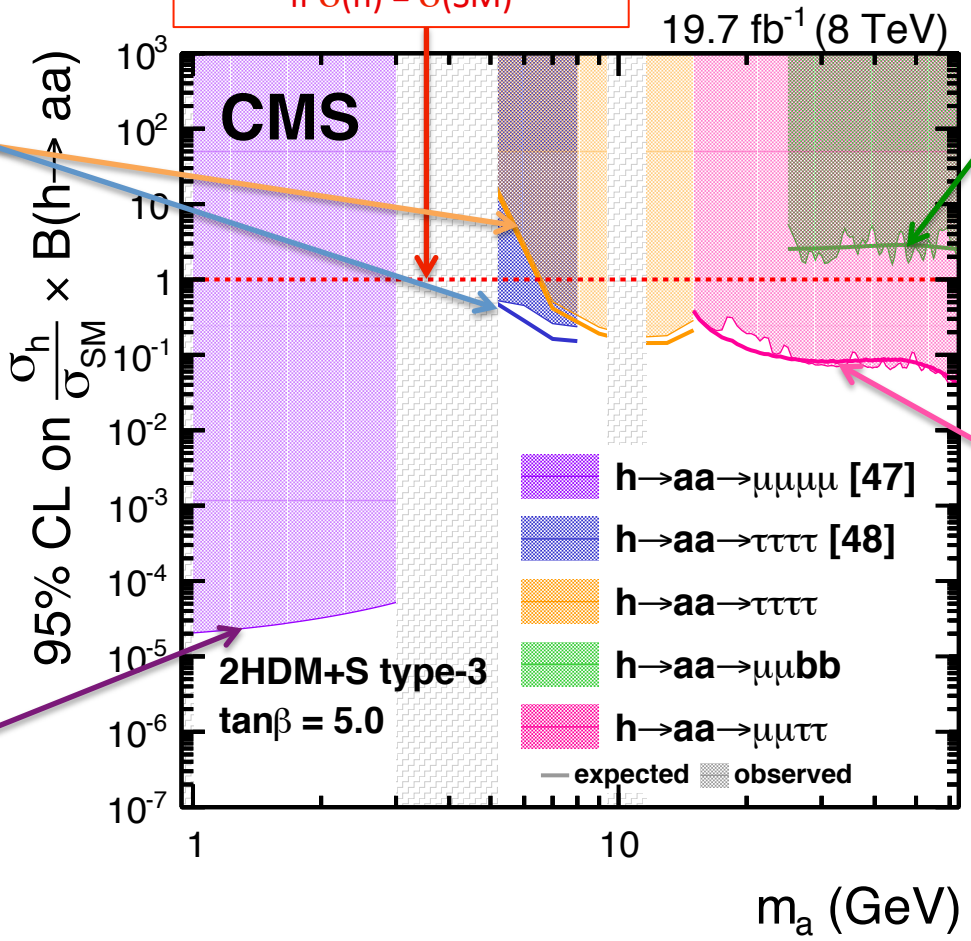
- This talk will mainly present results with 13 TeV searches.

Run1 legacy

Sensitivity to B(h → aa) = 1 if σ(h) = σ(SM)

h → aa → 4τ: Dominant decay mode if $m_a < 2m_b$.

Taus are collimated. Need specific boosted techniques



h → aa → 2μ2b: Favored by large B(a → bb) and narrow dimuon resonance

h → aa → 4μ: Dominant decay mode if $m_a < 2m_\tau$

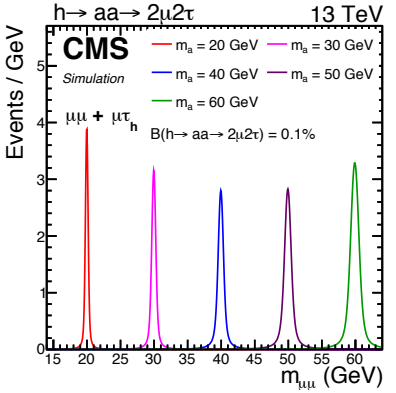
h → aa → 2μ2τ: Favored narrow dimuon resonance and low level of backgrounds

- CMS covered full m_a range in Run1 with h →aa → 4μ / 4τ / 2μ2τ / 2μ2b final states.
- Competitive ATLAS Run1 results exist with h → aa → 2μ2τ and aa → 4γ final states.

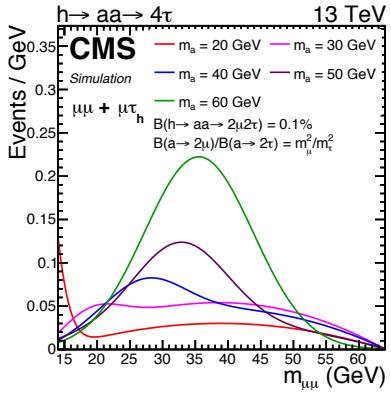
$h \rightarrow aa \rightarrow 2\mu 2\tau$ (CMS)

arXiv:1805.04865, Submitted to JHEP

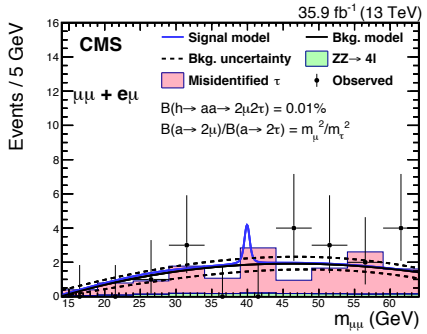
- Decay of $h \rightarrow aa \rightarrow \mu\mu\tau\tau$ is favored in 2HDM + s type III (highest BR for $\tan\beta > 1$).
- Motivation: di-muon has excellent mass resolution, di-tau reasonable mass resolution but has low backgrounds.
- 4 event categories: $\mu\mu$ + $e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$
- Backgrounds:
  - Irreducible background: comes from ZZ → 4l, estimated by simulation.
  - Reducible backgrounds: fake leptons or taus from jets (use fake rate method)
- Final observable is di-muon mass.

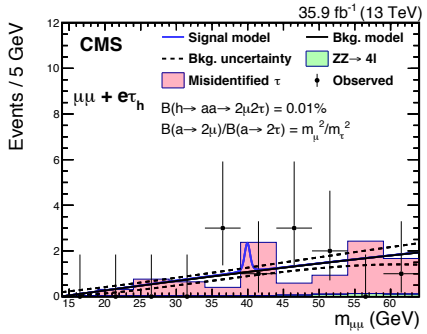


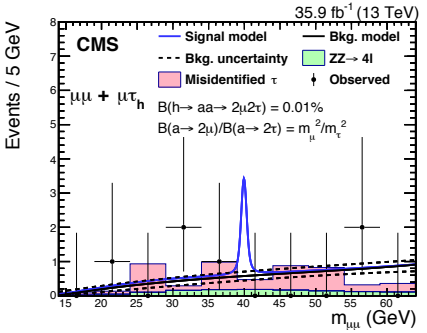
Signal is modeled by Voigt function

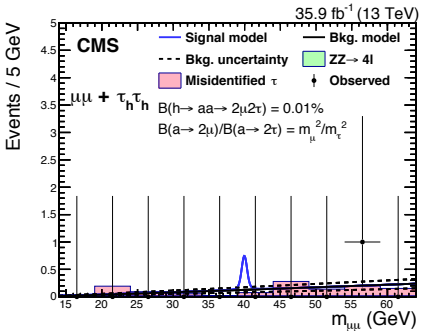


$h \rightarrow aa \rightarrow \tau\tau\tau\tau$ considered part of the signal



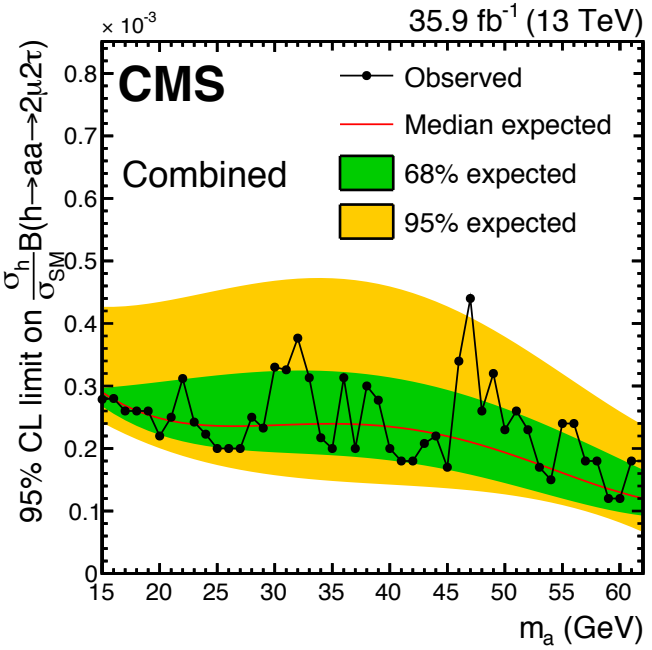




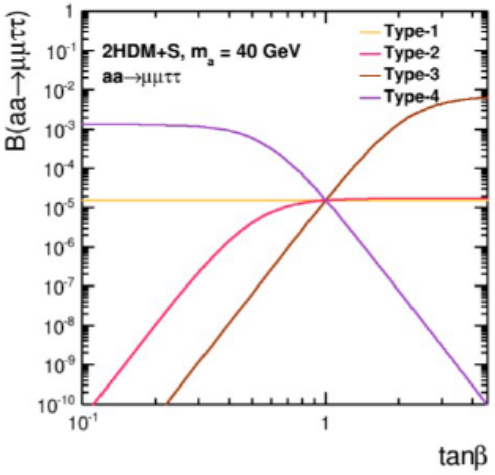


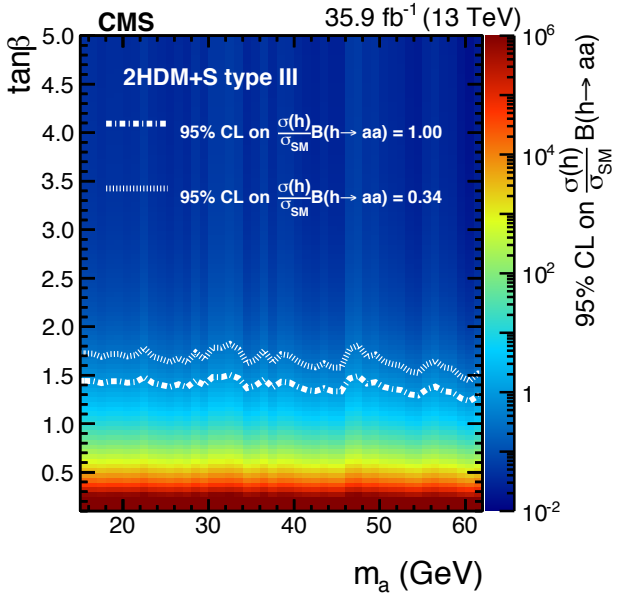
$h \rightarrow aa \rightarrow 2\mu 2\tau$ (CMS)

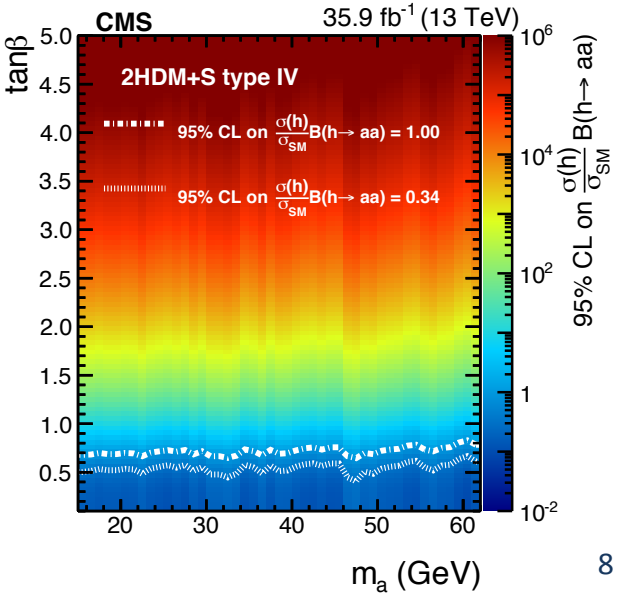
- Un-binned maximum likelihood fit in di-muon mass is performed to extract results.
- No significant excess is observed.
- Upper limits on BR(h→aa) as a function of tanβ, for 2HDM type III and IV:
  - limits as low as ~2 % in Type III
  - limits as low as ~20% in type IV



Observed limits on (σ_h/σ_{SM}) x BR(h→aa) in 2HDM+S type III (left) and type IV (right)



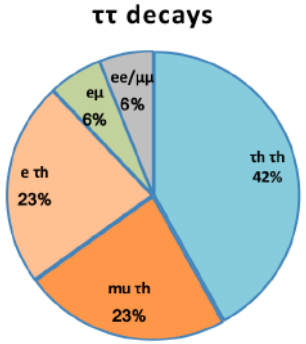




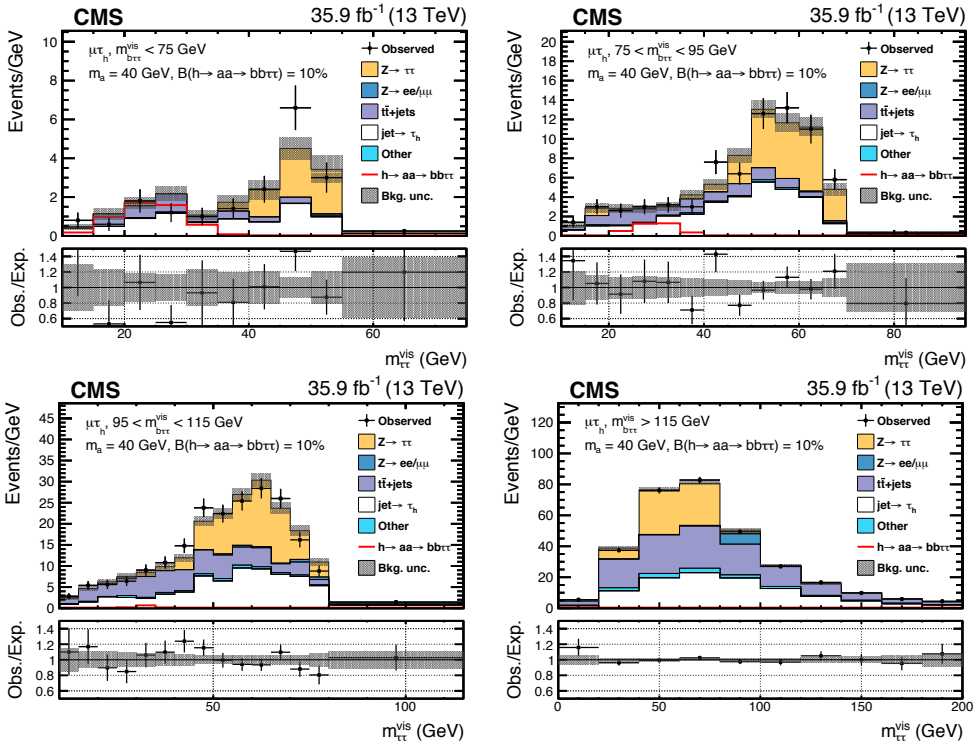
$h \rightarrow aa \rightarrow 2b2\tau$ (CMS)

arXiv:1805.10191, Submitted to PLB

- First time this final state is probed!
- Broad sensitivity expected due to enhanced BR of a→ττ and a→bb.
- Selection:
  - three di-tau final states: eμ, eτ_h, μτ_h
  - at least 1 b-tagged jet (medium CSV) with p_T > 20 GeV



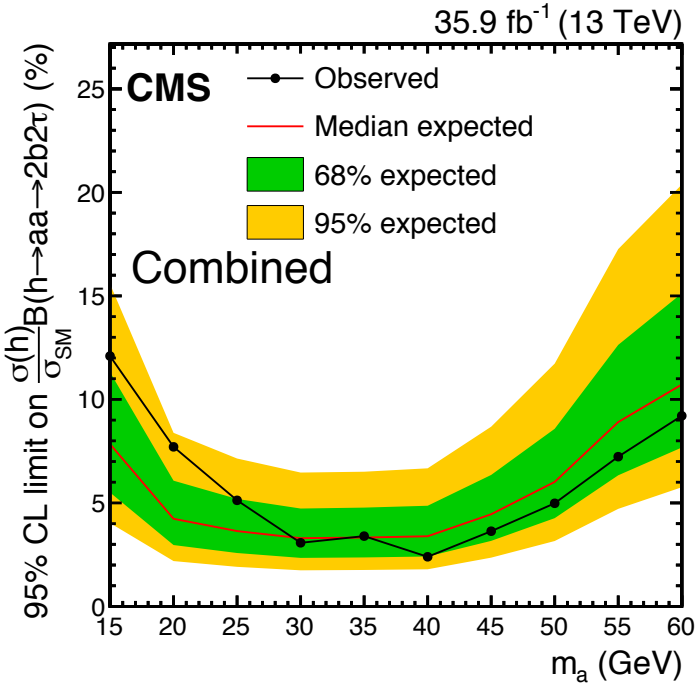
- Backgrounds with real taus (DY + jets, ttbar, VV) from simulation.
- Backgrounds with jets faking taus (QCD, W+jets) from data using jet to tau fake rate method.
- Final observable is di-τ($m^{vis}_{\tau\tau}$)
- Event categorization based on $m^{vis}_{\tau\tau b}$ to increase sensitivity.



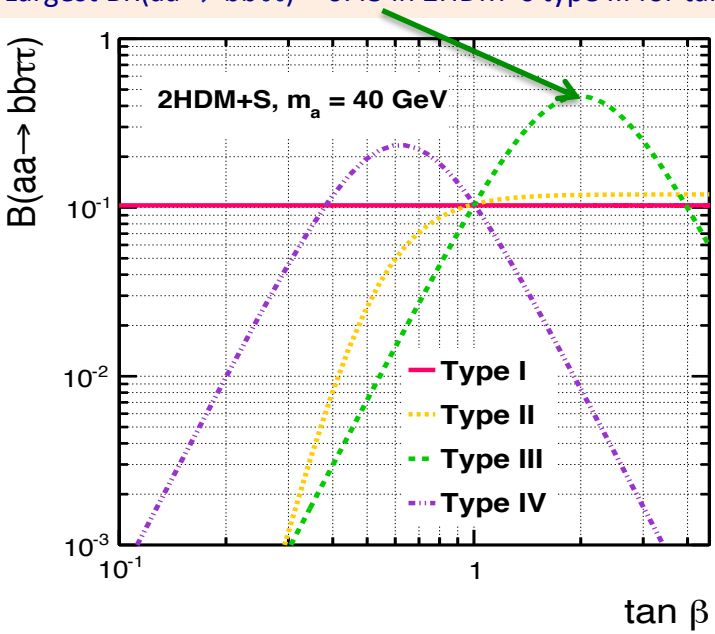
$h \rightarrow aa \rightarrow 2b2\tau$ (CMS)

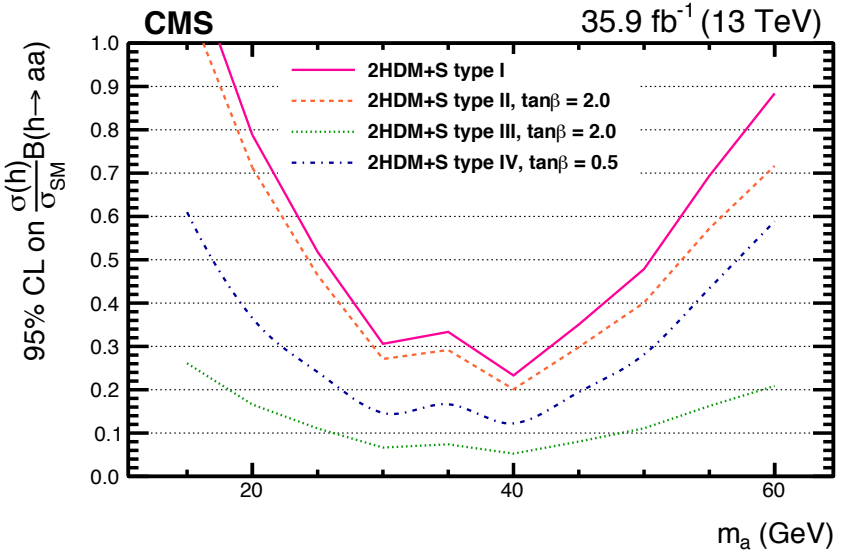
- Combined limit obtained by simultaneous fit of 12 channels/categories.
- Sensitivity is reduced at low $m_a < 30$ due to isolation inefficiencies of boosted di-τ system.
- Limit is much stronger on intermediate tanβ in 2HDM+s type III, and low tanβ in type IV.

Limits on (σ_h/σ_{SM}) x BR(h→aa→2τ2b)



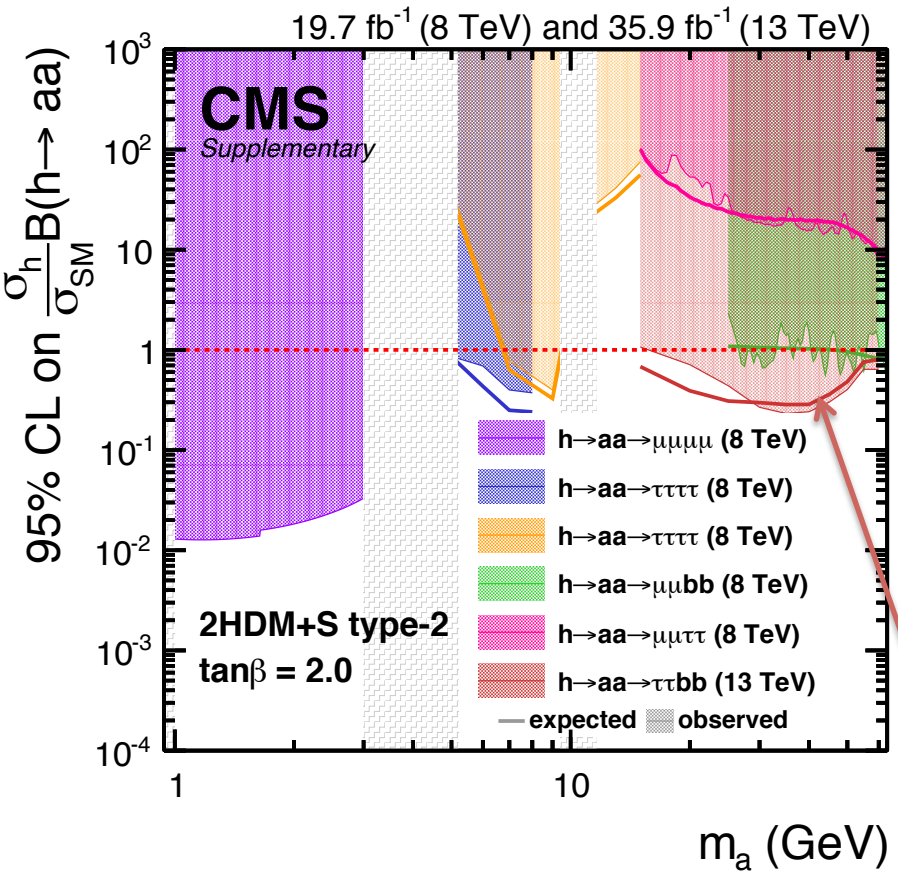
Largest BR(aa → bbττ)~=0.45 in 2HDM+s type III for tanβ=2



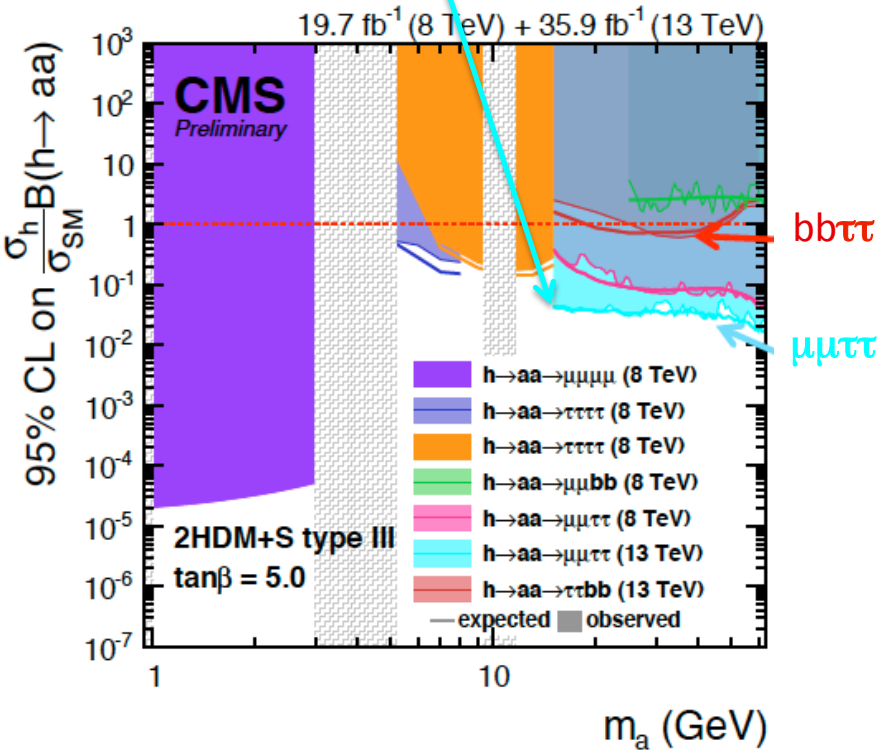


Run2 top-up summary

- 8 TeV + 13 TeV summary



CMS h → aa → μμττ limit improved by more than factor 2 wrt Run1

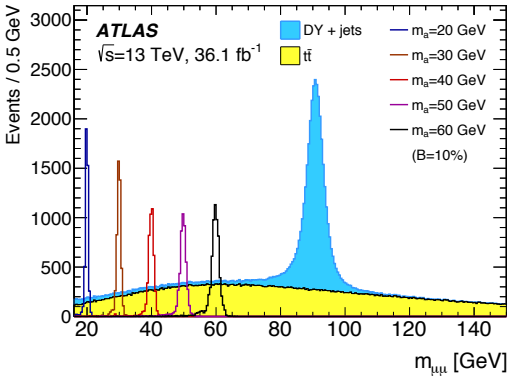


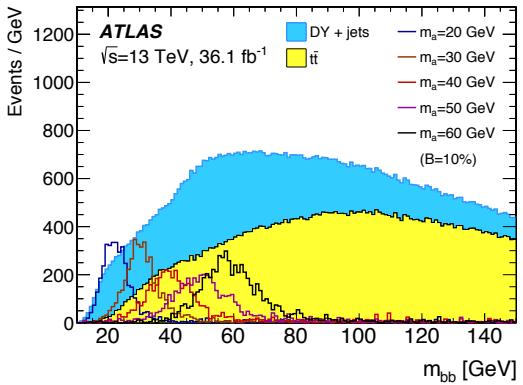
CMS h → aa → bbττ

$h \rightarrow aa \rightarrow 2b2\mu$ (ATLAS)

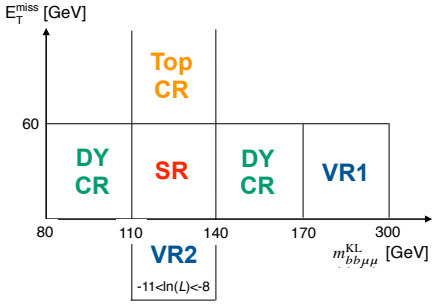
arXiv:1807.00539, Submitted to PLB

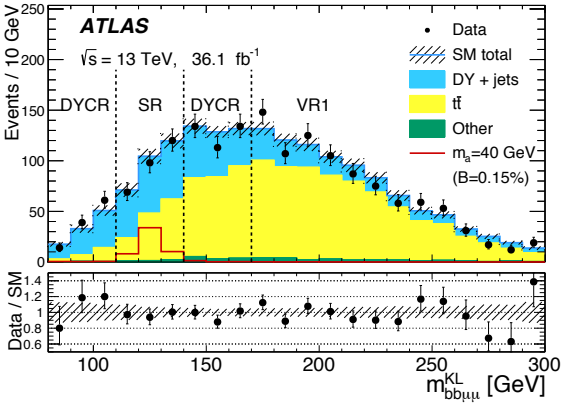
- Looked for in ggF, VBF modes.
- Selection:
  - exactly 2 b-tagged jets with $p_T^{jet} > 20$ GeV
  - exactly 2 OS muon pairs with $p_T^1 > 27$ GeV and $p_T^2 > 7$ GeV.
  - MET > 60 GeV



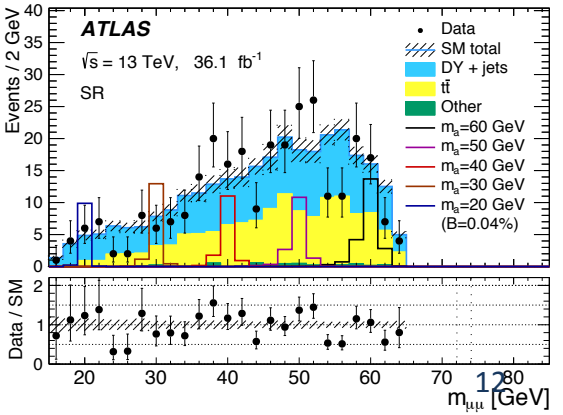


- Kinematic-likelihood (KL) fit is used to improve $m_{\mu\mu bb}$ resolution:
  - Using $m_{bb} \approx m_{\mu\mu}$ hypothesis
  - $|m_{\mu\mu bb} - m_H| < 15$ GeV





- Backgrounds constrained from dedicated Control Regions:
  - Top CR: inverting MET requirement < 60 GeV.
  - DY + jets CR: from $m_{\mu\mu bb}$ sidebands and zero b-tag.



- Simultaneous likelihood fit across SRs and CRs in $m_{\mu\mu bb}$.

h → aa → 2b2μ (ATLAS)

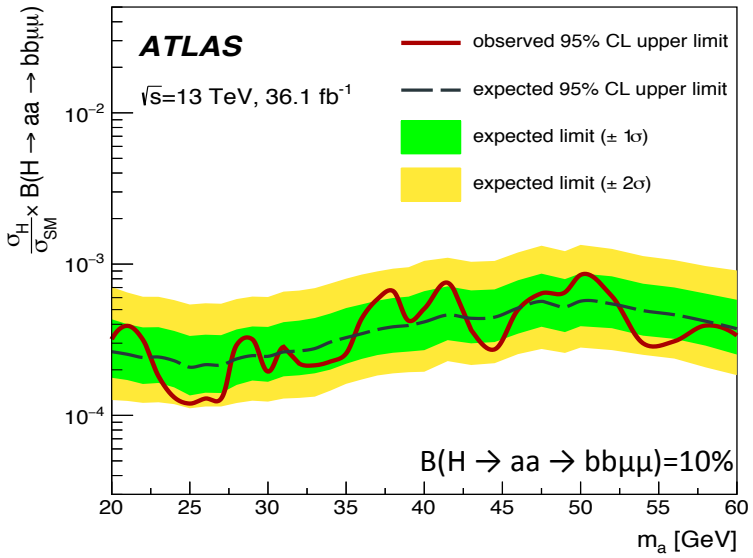
- Dominant systematics uncertainties:

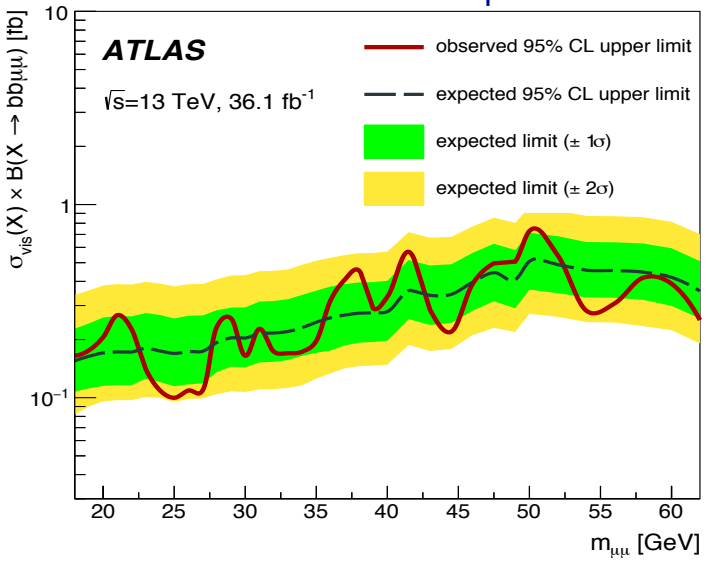
Source	Total background [%]	Signal [%]
MC statistics	2.4–4.9	2.3–4.6
b-tagging	0.6–1.5	17–19
Jet-energy resolution	0.3–2.9	5.2–8.4
Jet-energy scale	0.3–2.9	3.9–6.5
Muon-p_T resolution	0.1–2.2	0.3–1.2
Luminosity	< 0.01	2.1

Source	Total background [%]
DY: normalisation	9.3–15
DY: flavour composition	6.9–11
DY: background subtraction	0.4–2.4
$t\bar{t}$: hard-scatter generation	3.6–8.6
$t\bar{t}$: hadronisation/parton-shower	3.2–7.7
$t\bar{t}$: normalisation	2.1–5.0
$t\bar{t}$: ISR/FSR	1.0–2.4

- No significant deviations over SM expectations in the Signal Regions.
  - Set upper limits on signal yields as a function of $m_{\mu\mu}$ with the CL_s statistic method

Model independent





Limits on $(\sigma_H/\sigma_{SM}) \times B(H \to aa \to bb\mu\mu)$:
2×10^{-4} to 10^{-3} for a-boson mass: 20–60 GeV

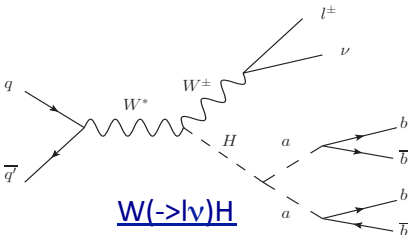
Upper limits on $\sigma_{vis}(X) \times B(X \to bb\mu\mu)$:
0.1 fb to 0.73 fb for $m_{\mu\mu}$ between 18-62 GeV

h → aa → 4b (ATLAS)

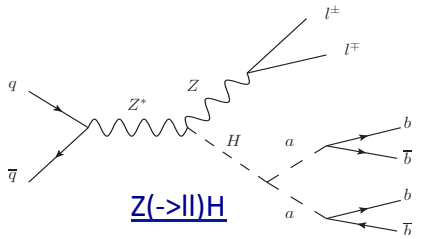
- WH and ZH production modes.
  - W/Z decay leptonically
  - ggF and VBF are difficult to trigger

- Binned BDT shape analysis. BDT input variables largely independent on the a mass signal hypothesis.

- Utilize dedicated control regions to validate Top (Wh) and DY+jets (Zh) background modeling.



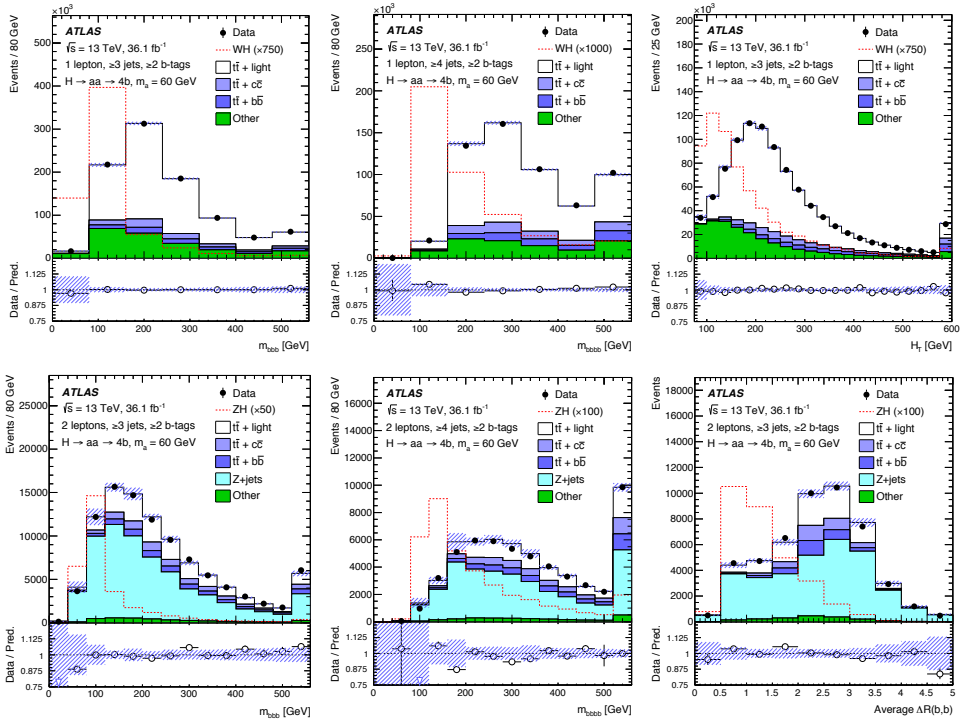
W(->lν)H

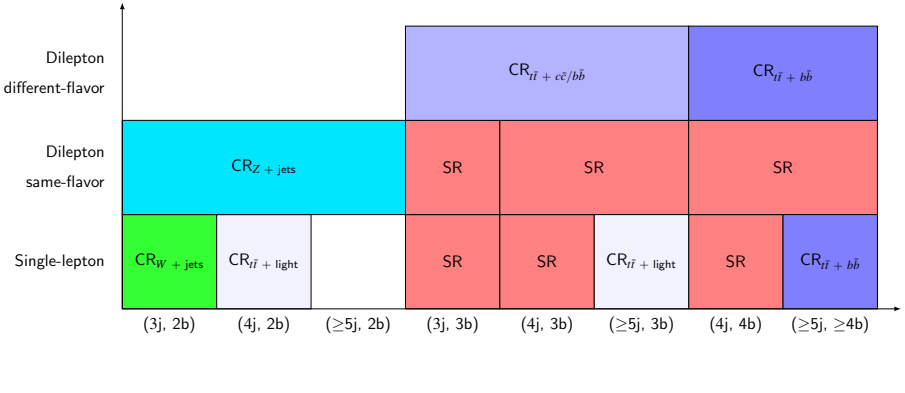


Z(->ll)H

Requirement	Single lepton	Dilepton
Trigger	single-lepton triggers	
Leptons	1 isolated	2 isolated, opposite-charge
Jets	≥ 3	
b-tagged jets	≥ 2	
Other	$E_{\mathrm{T}}^{\mathrm{miss}} > 25\ GeV$, $m_{\mathrm{T}}^{W} > 50\ GeV$	$85\ GeV < m_{\ell\ell} < 100\ GeV$

BDT input variables, examples

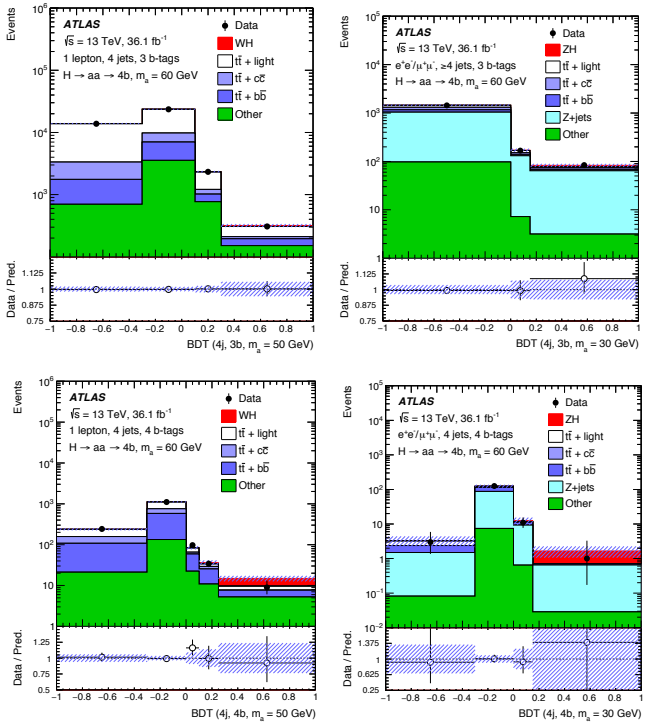




h → aa → 4b (ATLAS)

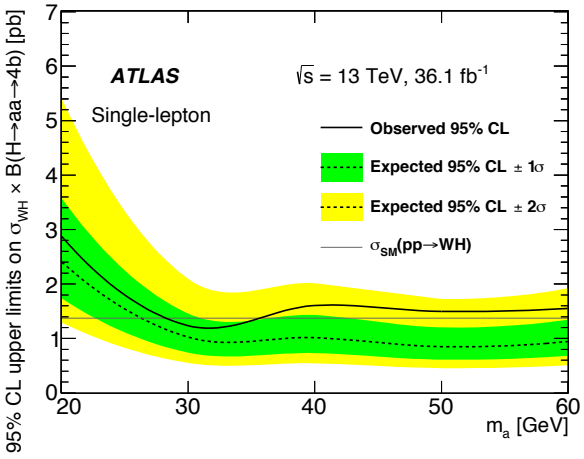
- Post-fit BDTs after the combined (simultaneous) fit to the single-lepton and di-lepton SRs and CRs.
- Dominant systematics:

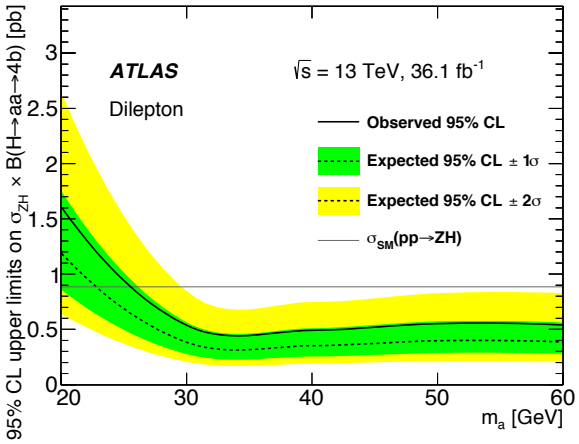
Systematic uncertainty	Impact on yield [%]						
	Single lepton				Dilepton		
	WH signal	$t\bar{t}$ + light	$t\bar{t} + c\bar{c}$	$t\bar{t} + b\bar{b}$	ZH signal	$t\bar{t} + b\bar{b}$	Z + jets
b-tagging efficiency	16	5	4	9	20	14	17
c-tagging efficiency	1	5	9	3	7	1	1
Light-jet-tagging efficiency	2	16	5	2	1	3	1
Theoretical cross-sections	–	5	5	5	–	8	–
$t\bar{t}$: modelling	–	5	35	45	–	19	–
$t\bar{t}$+HF: normalization	–	–	31	33	–	38	–
$t\bar{t}$+HF: modelling	–	–	10	5	–	7	–
Z + jets: normalization	–	–	–	–	–	–	38
Signal modelling	7	–	–	–	10	–	–
Displaced b-tagging	5–8	–	–	–	5–8	–	–
Total	33–34	32	75	58	30–31	32	36

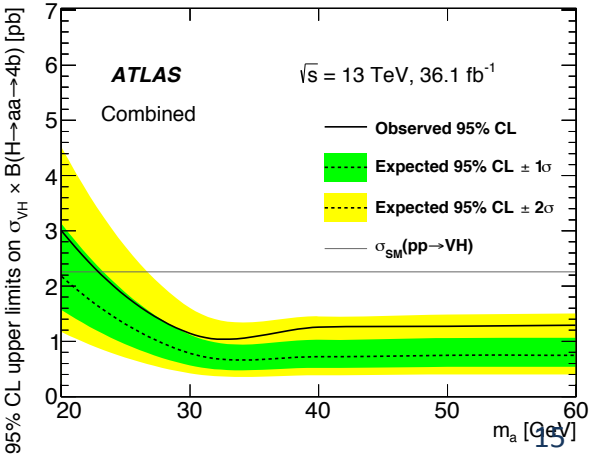


- Higher sensitivity for Zh analysis due to larger S/B: ≈ 4% (Zh) vs 0.6% (Wh) for m_a = 60 GeV.
- Low m_a points (<30) limited by signal acceptance.

Assume SM NNLO σ_{SM}(Wh)=1.37pb and σ_{SM}(Zh)=0.88 pb

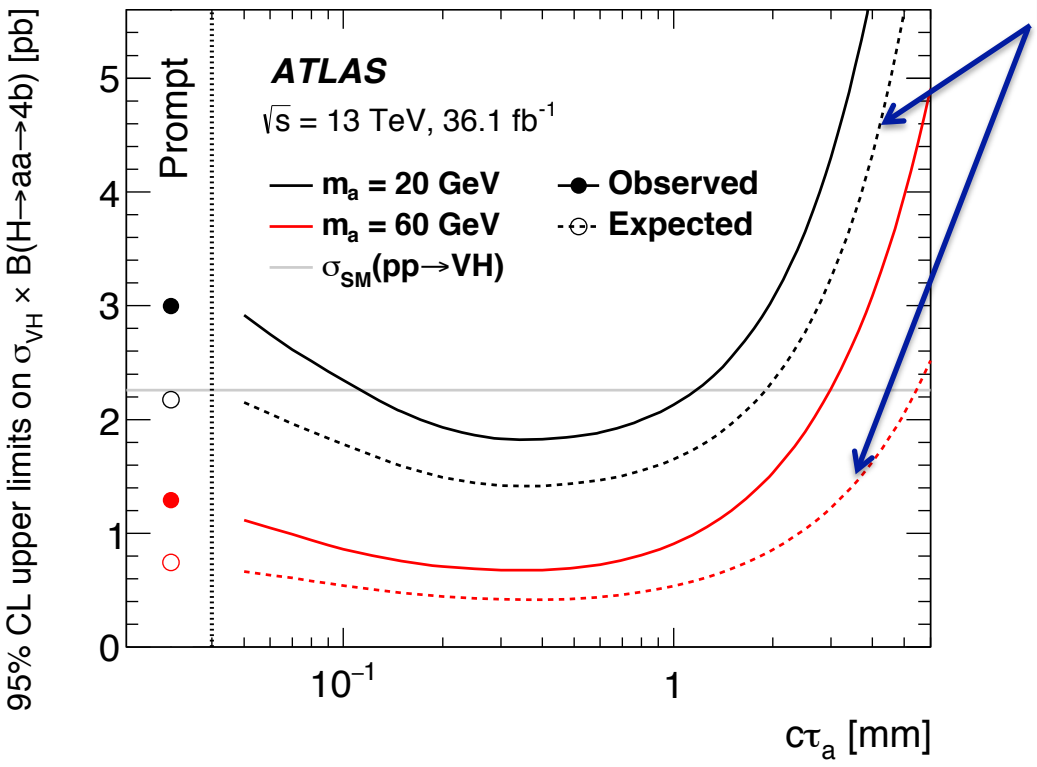






h → aa → 4b long-lived

- New Physics may be long-lived as well
  - motivated by models of neutral naturalness, where the a-bosons are long-lived.
- Re-interpretation of results in terms of a long-lived signal (i.e. same backgrounds)
  - Additional systematic uncertainty to account for a discplacement-dependent mis-modeling of the b-tagging efficiency (5 – 8 %).



Long-lived h → aa → 4b limits

- Slightly improved limits up to a boson lifetimes ~ 0.5mm due to enhanced b-tagging efficiency.
- Best limits are 1.8 pb (m_a = 20 GeV) and 0.68 pb (m_a = 60 GeV), at $c\tau_a$ ~ 0.4mm.

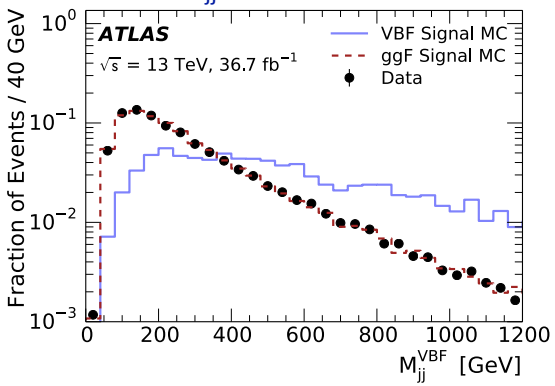
$h \rightarrow aa \rightarrow 2\gamma 2g$ (ATLAS)

Phys. Lett. B 782 (2018) 750
arXiv:1803.11145

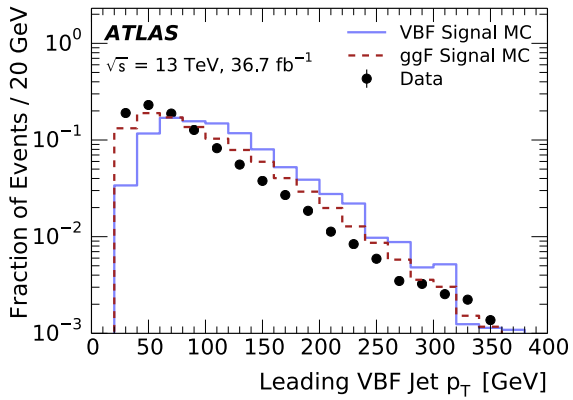
- Relevant to models where fermionic decays are suppressed and the a boson decays only into photons or gluons.

- VBF Higgs boson production
  - ggF is overwhelmed by $\gamma\gamma$ + multijet background, VH needs ~300 fb^{-1} at the LHC.
- Selection:
  - di-photon trigger, >=2 photons with $p_T^{\gamma 1} > 40$ GeV and $p_T^{\gamma 2} > 30$ GeV.
  - >=4 jets, 2 jets with largest m_{jj} (m_{jj}^{VBF}) are referred to as VBF jets.

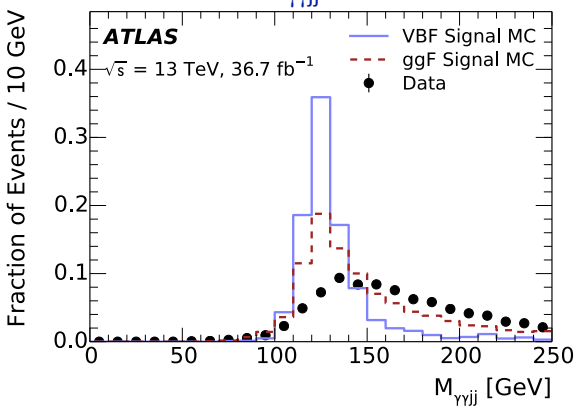
$m_{jj}^{VBF} > 500$ GeV



$p_T^{j1} > 60$ GeV



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



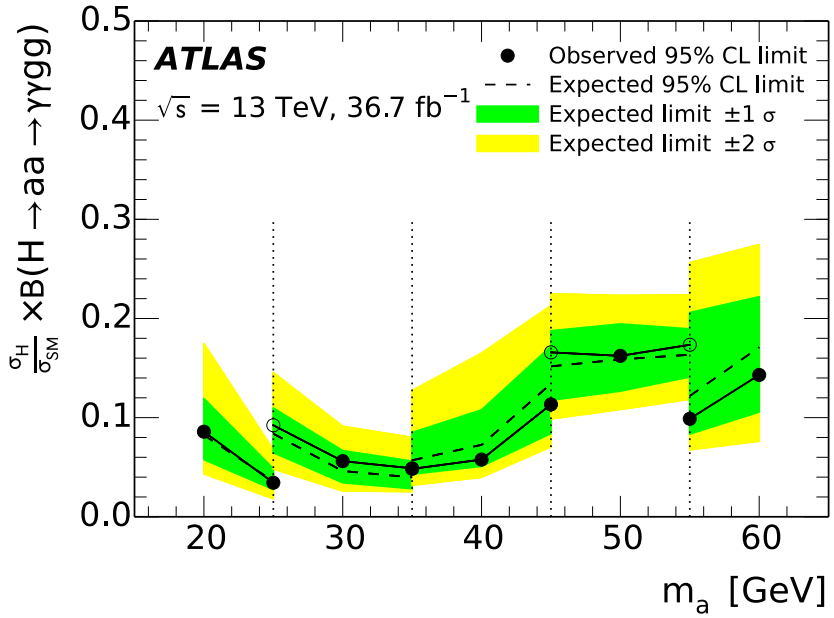
- Backgrounds: $\gamma\gamma$ + multijet with 2 misidentified photons; estimated from data based on 2D sidebands in photon ID versus $|m_{jj} - m_{\gamma\gamma}|$ observables.

$h \rightarrow aa \rightarrow 2\gamma 2g$ (ATLAS)

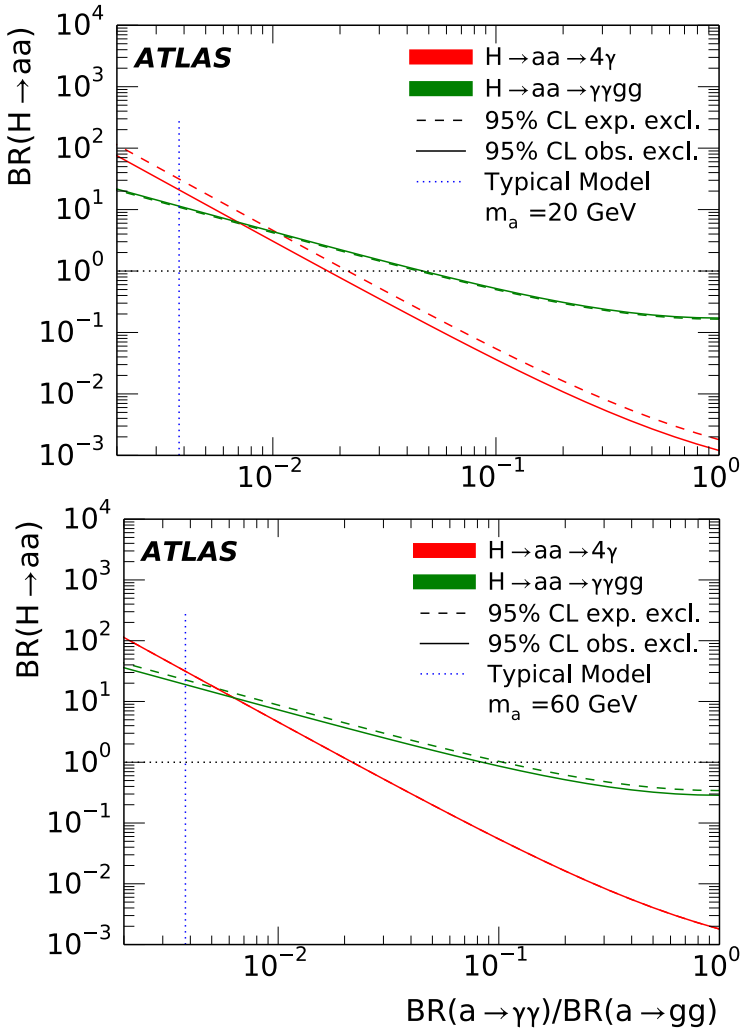
- Results extracted via a max likelihood fit to data simultaneously across the SRs and sidebands.
- Dominant systematic uncertainties:

Source of Uncert.	$m_{\gamma\gamma}$ regime 1 $m_a = 20$ GeV	2 $m_a = 30$ GeV	3 $m_a = 40$ GeV	4 $m_a = 50$ GeV	5 $m_a = 60$ GeV
Statistical	0.73	0.51	0.89	1.13	0.92
Closure	0.44	0.27	0.39	0.64	0.89
Modelling	0.35	0.34	0.46	0.42	0.65
Jet	0.58	0.38	0.25	0.90	0.71
Photon	0.06	0.05	0.10	0.12	0.13
Lumi and Pile-up	0.06	0.04	0.27	0.14	0.32

- Limits on (σ_h/σ_{SM}) x BR(h→aa→2γ2g) range from 3.1 pb to 9.0 pb depending on a boson mass.



Limit on B(H→ aa) as a function of B(a→ γγ)/B(a→ jj), comparing with ATLAS Run1 H→ aa → γγγγ

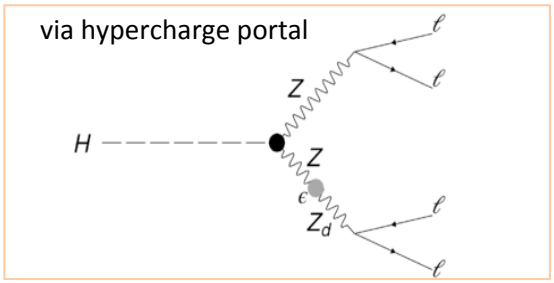


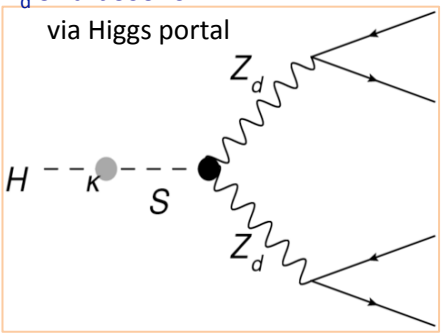
$h \rightarrow 2Z_d$ / ZZ_d / $aa \rightarrow 4l$ (ATLAS)

arXiv:1802.03388, JHEP06(2018)166

- Analysis targeting also $H \rightarrow ZZ_d$ and $H \rightarrow Z_dZ_d$. In 2HDM+s, large branching ratio for $H \rightarrow aa \rightarrow 4\mu$ for $m_a < 2\ m_\tau$.

X: intermediate dark vector bosons Z_d or a bosons

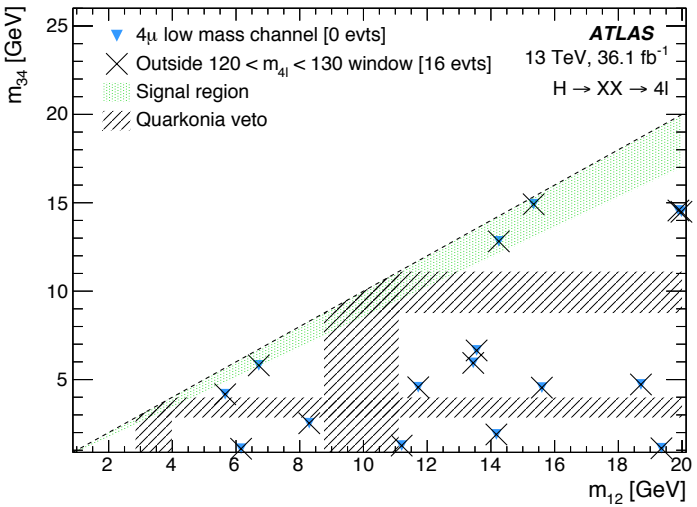




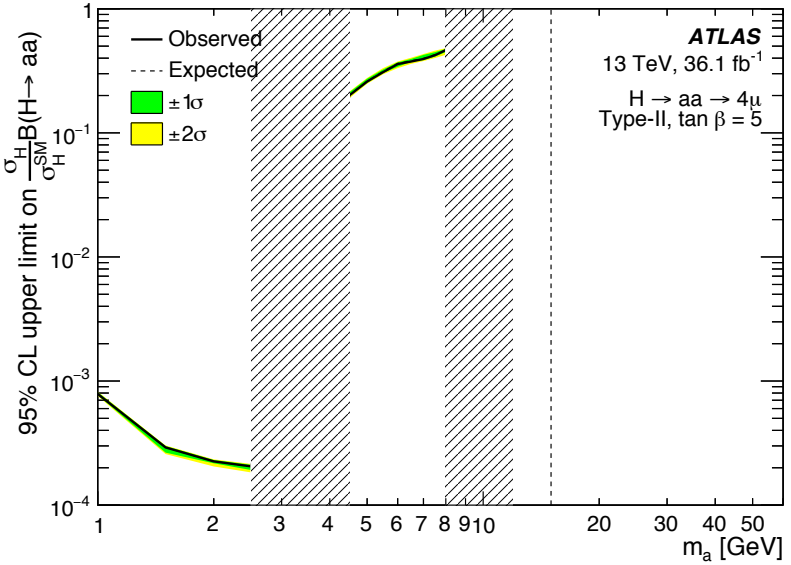
- Clean signal can access also big ggF cross section.

- Data collected with a mixture of single-, double- and triple-lepton triggers.

- No signal event passing the low mass selection for an expectation of 0.4 ± 0.1 events.

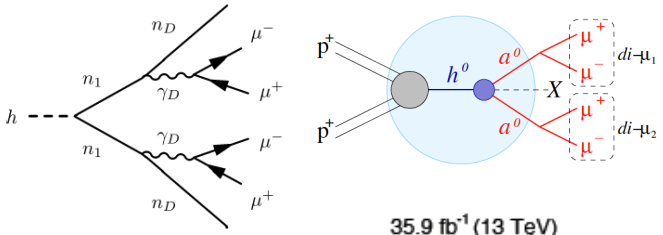


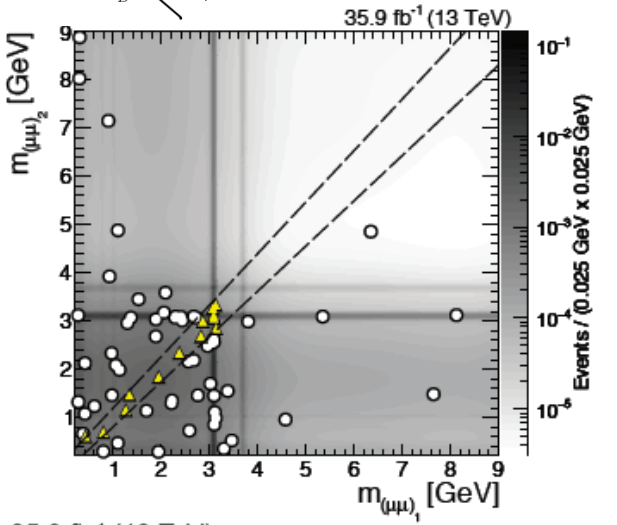
Upper limit on (σ_h/σ_{SM}) x B(H→ aa)

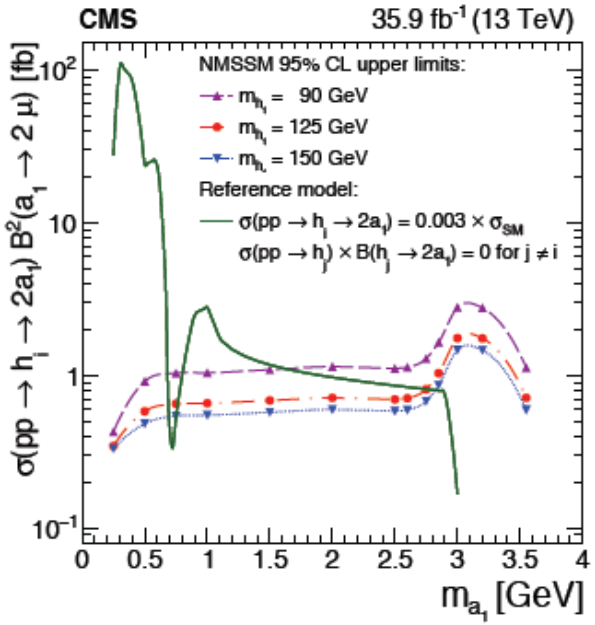


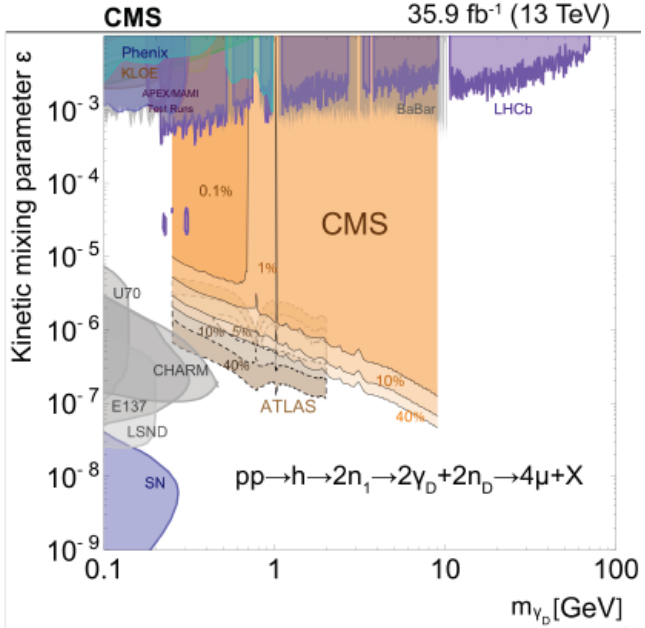
h → aa → 4μ (CMS)

- Search targets NMSSM (a → μμ) + Dark SUSY models.
- Ad-hoc triggers for discplaced muon signatures + dedicated reconstruction for non-pointing muons.
- Backgrounds: bb and prompt J/ψ estimated from data, EWK -> 4μ from simulation.
- Observe 13 events for a total background expectation of 9.90 ± 1.24 (stat.) ± 1.84 (syst.).









γ_D decays to μμ,
γ_D may be long lived

Summary and outlook

- Rich ATLAS and CMS program to search for exotic decays of the SM-like Higgs boson in two light bosons (a) covering almost full m_a range.
  - m_a ~< 15 GeV: boosted speudo-scalars, aa → 4μ / 4τ decays dominant
  - m_a >~ 15 GeV: decays to heavier fermions (a → ττ, a → bb) are favored

- Experimental results typically interpreted in 2HDM+s or NMSSM models, as a function of m_a and tanβ.
  - But h → aa decays can be motivated too in dark matter models. Recent theory work on Higgs exotic linking to dark matter: https://arxiv.org/abs/1712.03974

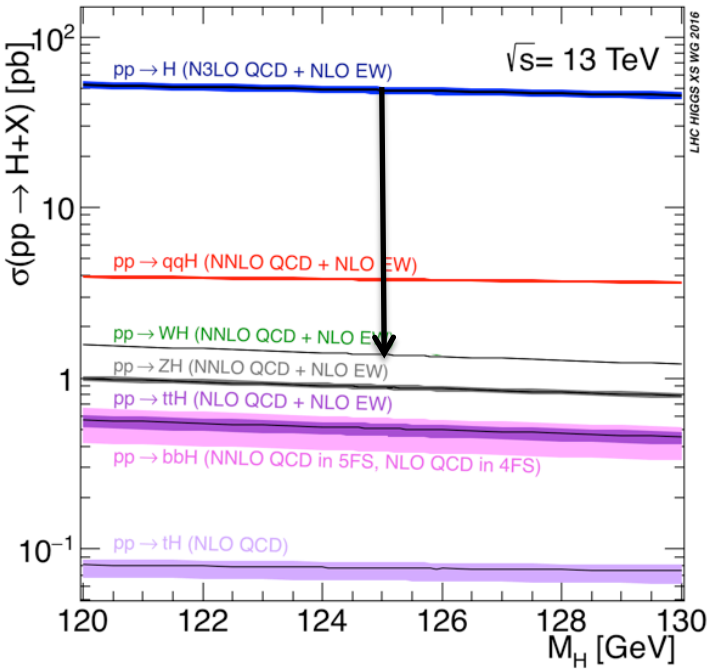
- No significant excess seen in any of the channels at 8 + 13 TeV, but exclusion limits much improved during the Run2 luminosity top-up.

- Anticipated LHC data up to 3000 fb^{-1} at 13 TeV will contain $O(10^8)$ Higgs bosons allowing branching ratios as small as 10^{-7} to be probed.
  - Many new results in h → aa awaited with full Run2 luminosity and beyond.

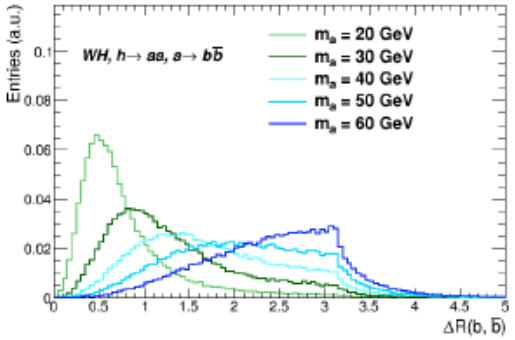
Backups

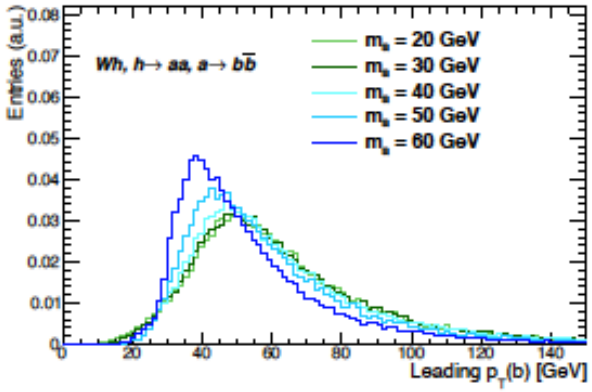
h → aa → 4b

- For signals with Yukawa-like couplings, BR(a → bb) dominates when kinematically allowed ($m_a > 2m_b$).
- ggF, VBF production modes overwhelmed by strong production of four b-jets.
  - Handle with VH mode and leptonically decayed W or Z boson.



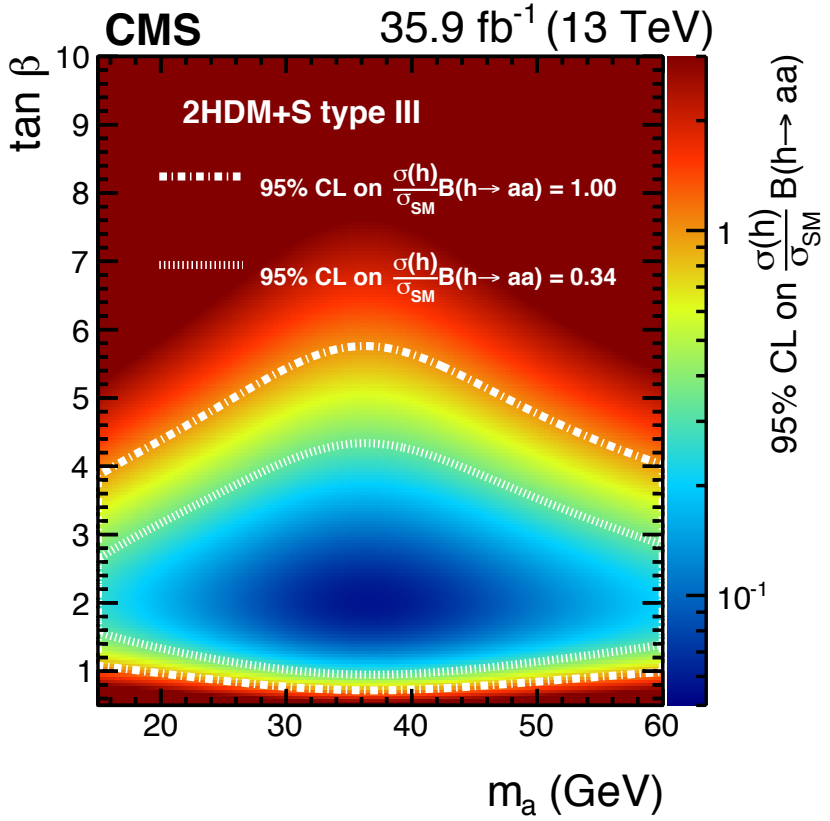
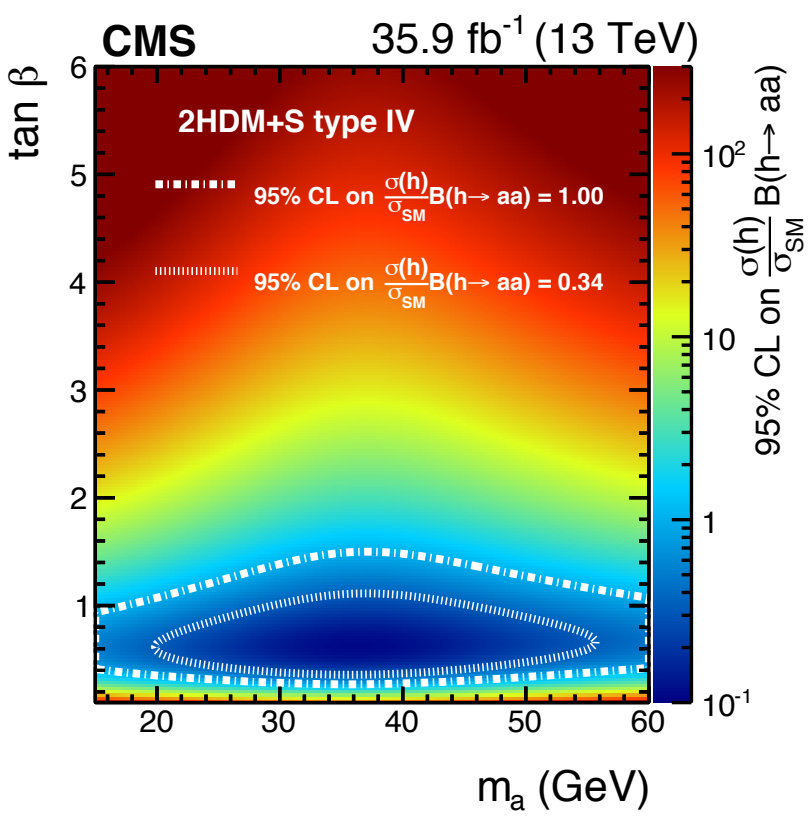
Loose one order of magnitude due to cross section





Soft signal: sensitivity can be lost due to p_T thresholds…

- **H → aa → (bb)(bb)** very well motivated search but also very challenging.

$h \rightarrow aa \rightarrow 2b2\tau$ interpretation, scan in tanβ

- Limit in type III and type IV 2HDM+S strongly depend on tanβ.