Searches for exotic visible Higgs boson decays at CMS and ATLAS

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on behalf of the ATLAS and
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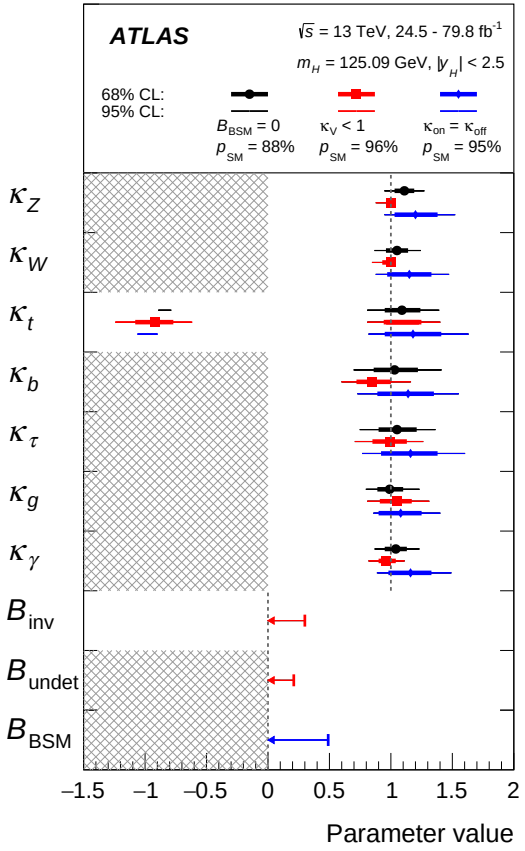
Higgs Couplings 2019, Oxford, UK

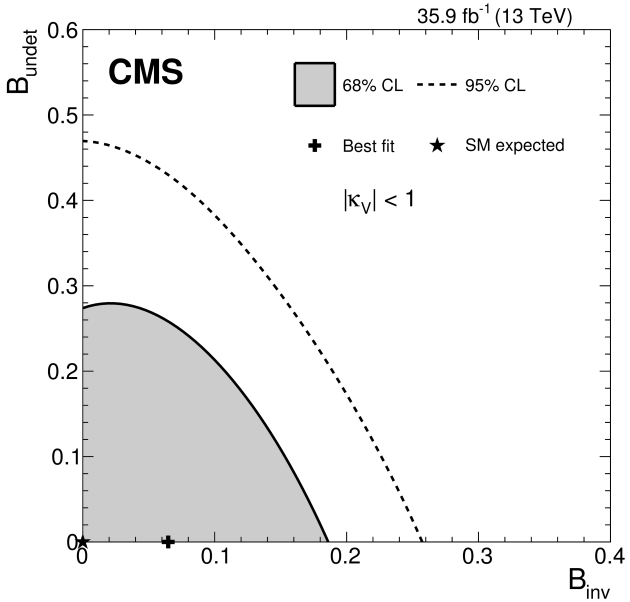
MOTIVATION

- Since the Higgs boson discovery in 2012, all measurements in agreement with the SM predictions
- SM Higgs boson width very narrow, $\sim\ 4\ \mathrm{MeV}$, much lower than the sensitivity of LHC
- Current constraints on BSM decays relatively loose, $\mathcal{B}(\mathrm{h} \to \mathrm{BSM}) < 34\%$
- Exotic Higgs decays predicted in many BSM theories with extended Higgs sector

arXiv:1909.02845



Eur. Phys. J. C 79 (2019) 421



8 TeV	13 TeV
$\mathrm{B_{BSM}} < 0.34$	$\mathrm{B_{inv}} < 0.30$ $\mathrm{B_{undet}} < 0.21$
	$\mathrm{B_{inv}} < 0.22$ $\mathrm{B_{undet}} < 0.38$

MOTIVATION

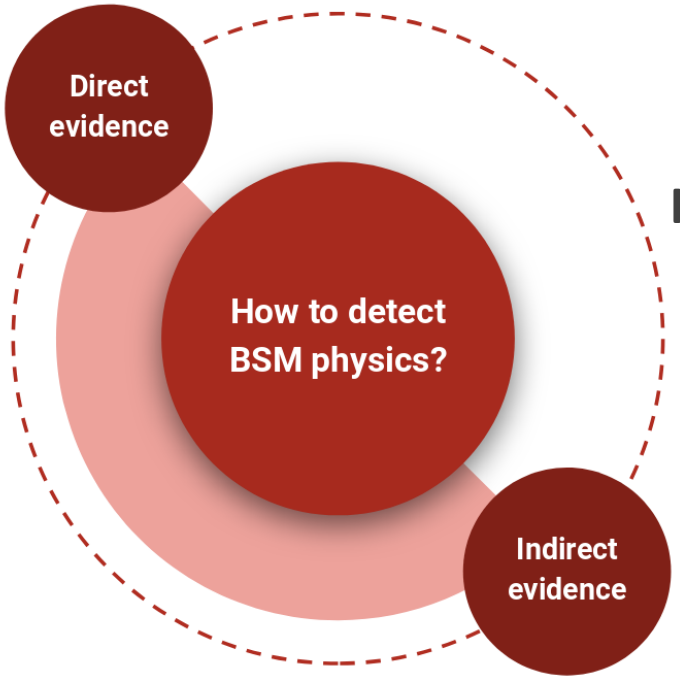
Search for BSM decays of the Higgs boson though

Rare decays
Predicted by the SM

Lepton flavour violating decays
Forbidden in the SM

Invisible decays
In the SM, only via
$\mathrm{H} \to \mathrm{ZZ}^* \to 4\nu$, $\mathcal{B}_{inv} < 0.1\%$

Decays to light (pseudo-)scalars
$\mathrm{h} \to \mathrm{aa} \to X\bar{X}Y\bar{Y}$
Predicted in many SM extensions
(2HDMs, 2HDM+S)



Search for deviations in the Higgs boson couplings

Precision measurements needed
model-specific approach

$\mathrm{h}(125) \to \mathrm{a}_1\mathrm{a}_1 \to X\bar{X}Y\bar{Y}$ in ATLAS & CMS

Signatures

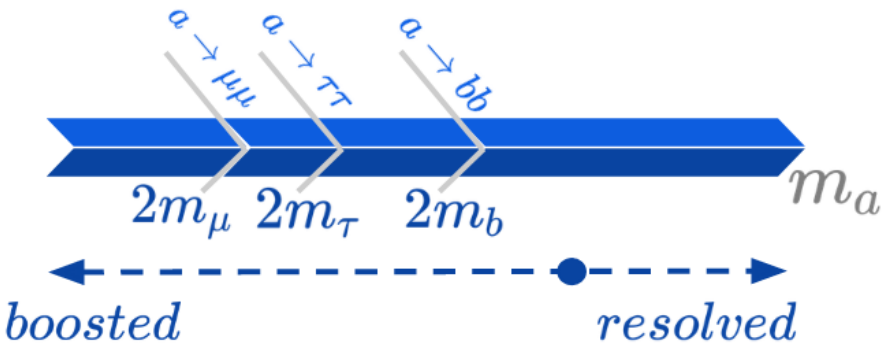
$\mathrm{a} \to \mathrm{bb}$: large BR, low $\mathrm{S/B}$, hard to trigger, low identification efficiency, high p_{T} thresholds

$\mathrm{a} \to \tau\tau$: large BR, low τ_{h} identification efficiency, high p_{T} thresholds

$\mathrm{a} \to \mu\mu$: low BR, high $\mathrm{S/B}$, excellent mass resolution, easy to trigger & identify

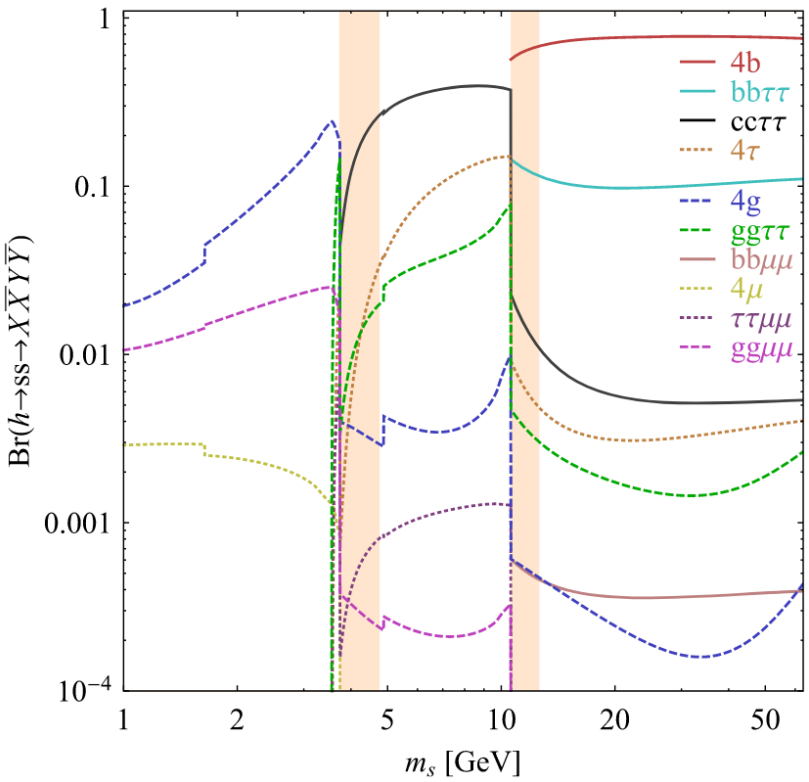
Challenging final states

- Decay products soft in p_{T} and can overlap



- ATLAS & CMS increase sensitivity with sophisticated analysis techniques

SM+S benchmark

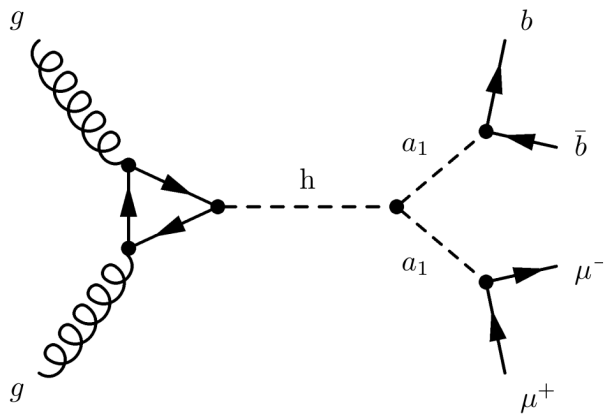


Phys. Rev. D 90, 075004 (2014)
arXiv:1312.4992

$\mathrm{h}(125) \to \mathrm{a_1 a_1} \to \mu\mu\mathrm{bb}$

✓ Large $\mathcal{B}(\mathrm{a} \to \mu\mu)$ in models with enhanced lepton couplings (Type-III 2HDM)

- $20 < \mathrm{m_{a_1}} < 62.5$ (60) GeV for CMS (ATLAS)
- Higgs production via ggF & VBF
- Main background from $\mathrm{Z} + \mathrm{jets}$ and $\mathrm{t\bar{t}}$



Baseline selections

- 2 isolated muons of opposite charge
- 2 b-jets
- $\mathrm{m_{bb}} \simeq \mathrm{m}_{\mu\mu}$ & $\mathrm{m_{bb\mu\mu}} \simeq \mathrm{m_h}$:

  CMS : $\chi^2 = \chi^2_{\mathrm{bb}} + \chi^2_{\mathrm{h}}$

  $\chi_{\mathrm{bb}} = (\mathrm{m_{bb}} - \mathrm{m}_{\mu\mu})/\sigma_{\mathrm{bb}}$

  $\chi_{\mathrm{h}} = (\mathrm{m}_{\mu\mu\mathrm{bb}} - \mathrm{m_h})/\sigma_{\mathrm{h}}$

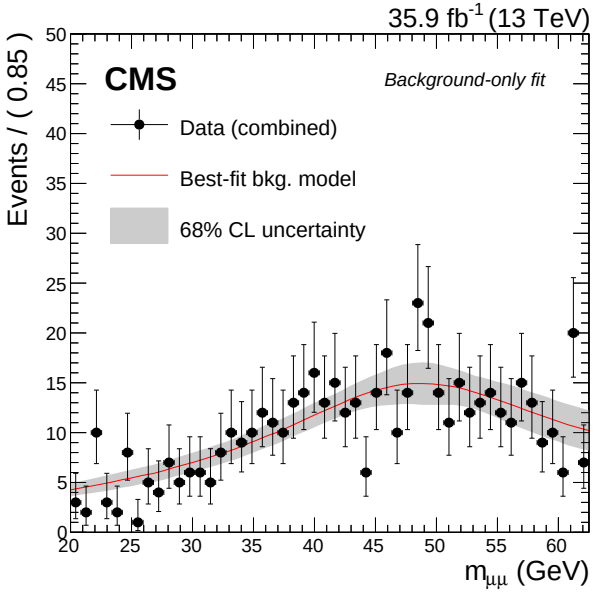
  ATLAS : kinematic-likelihood (KL) fit
- $\mathrm{E_T^{miss}} < 60$ GeV to suppress $\mathrm{t\bar{t}}$

ATLAS EXPERIMENT	Phys. Lett. B 790 (2019) 1 arXiv:1807.00539
CMS	Phys. Lett. B 795 (2019) 398 arXiv:1812.06359

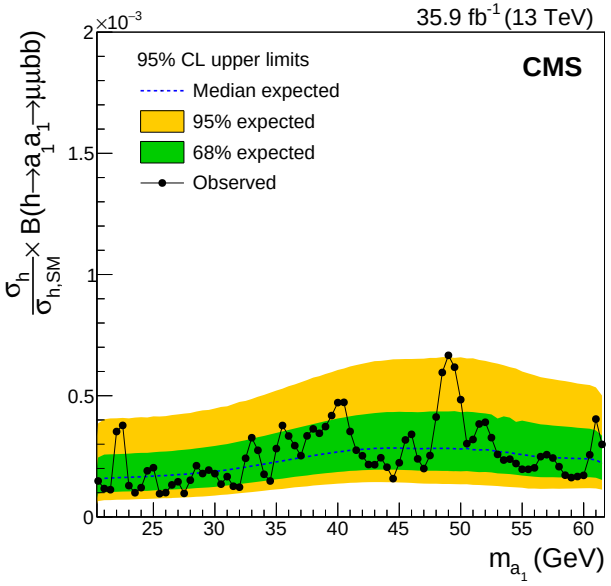
- An excess above the SM background is searched in the $\mathrm{m}_{\mu\mu}$ distribution

- $\chi^2 < 5$ ensures 64% signal efficiency & 95% background rejection
- Event categorisation (3 categories) based on the b-tagging working points (WPs)
- Unbinned fit to $\mathrm{m}_{\mu\mu}$ distribution in data used to model signal & background shape
- Background estimated in data using control regions (CRs) defined by inverting the χ^2 requirement

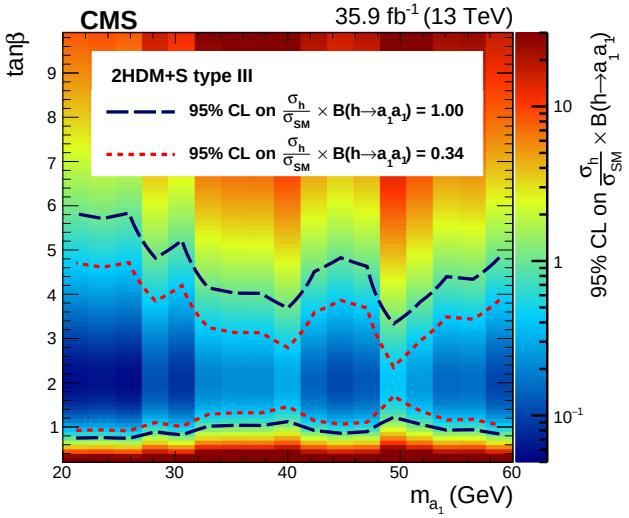
Inclusive



$\frac{\sigma_{\mathrm{h}}}{\sigma_{\mathrm{h,SM}}} \times \mathcal{B}(\mathrm{h} \to \mathrm{a_1 a_1} \to \mu\mu\mathrm{bb})$



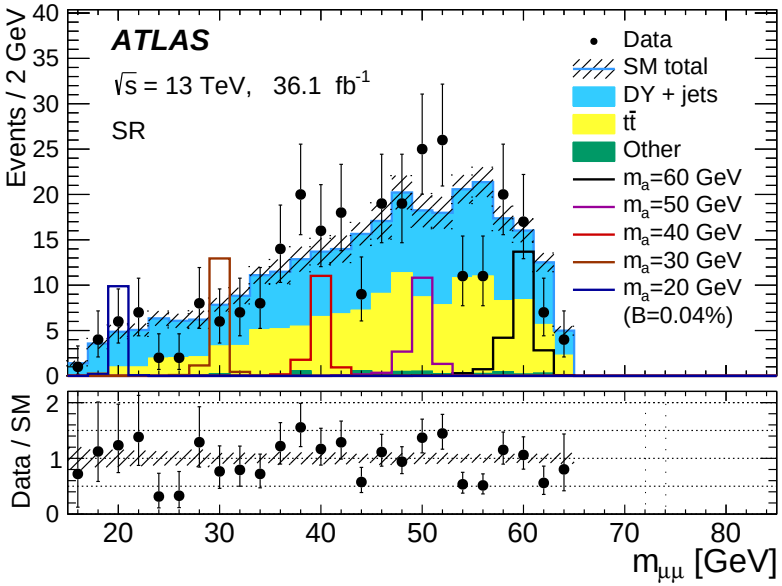
Type-III 2HDM+S



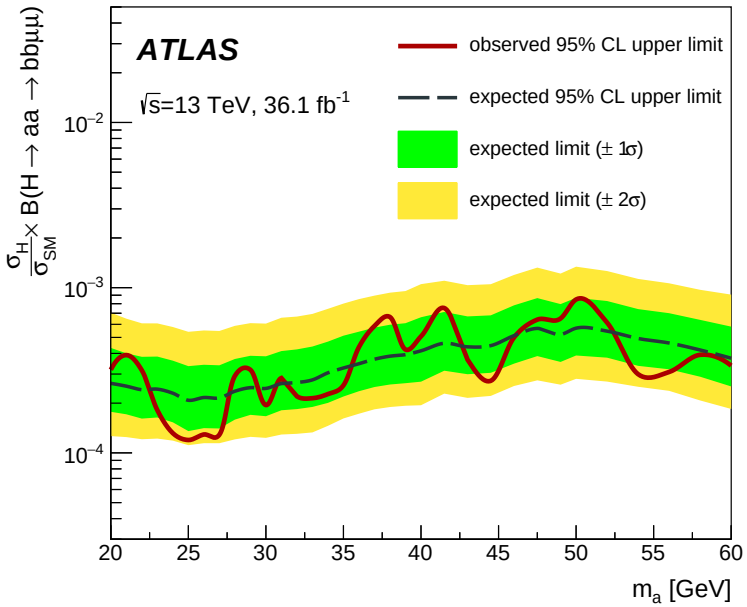
$\mathcal{B}(\mathrm{h} \to \mathrm{a_1 a_1} \to \mu\mu\mathrm{bb}) < (1-7) \times 10^{-4}$	(Obs.)
$\mathcal{B}(\mathrm{h} \to \mathrm{a_1 a_1} \to \mu\mu\mathrm{bb}) < (1-3) \times 10^{-4}$	(Exp.)

- KL fit improves the $m_{bb\mu\mu}$ resolution by a factor of two
- Main background ($Z + jets$ & $t\bar{t}$) estimated in data
- Control regions, defined by inverting E_T^{miss} selection ($t\bar{t}$ CR) and reconstructed $m_{bb\mu\mu}$ window (DY CR), used to constrain the background contribution in the signal region

$m_{\mu\mu}$ in Signal Region



$\frac{\sigma_H}{\sigma_{SM}} \times \mathcal{B}(H \to a_1 a_1 \to bb\mu\mu)$



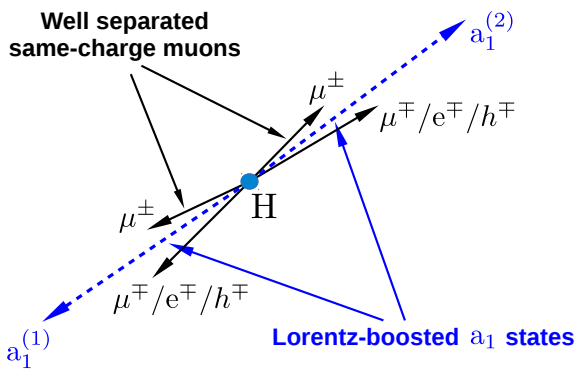
$\mathcal{B}(h \to a_1 a_1 \to \mu\mu bb) < (1.2 - 8.4) \times 10^{-4}$ (Obs.)

✓ Up to 90% $\mathcal{B}(\mathrm{a} \to \tau\tau)$ in Type-II 2HDM+S for large values of $\tan\beta$

- $4 < \mathrm{m_{a_1}} < 15$ GeV
- Higgs production via ggF, VBF, VH & $\mathrm{t\bar{t}H}$

- Identify highly Lorentz-boosted μ/τ pairs with overlapping decay products
- Main background from QCD multijet, diboson & top-quark production

$\mathrm{a_1} \to \tau_\mu \tau_{1-\mathrm{prong}}$

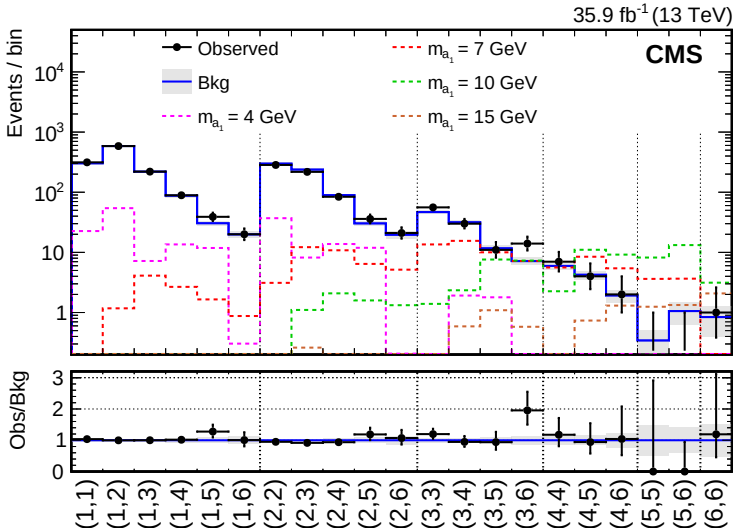


Signal searched in events with:

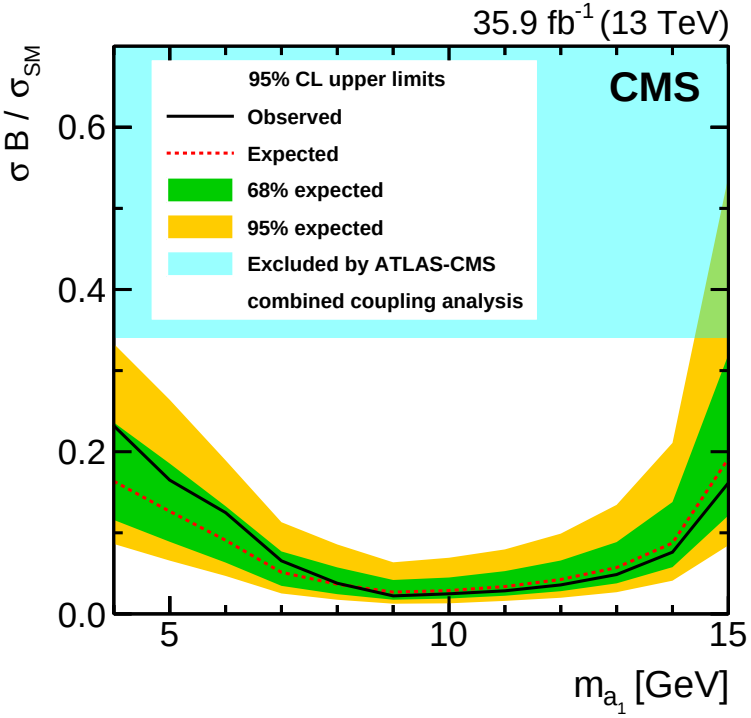
- Two same-sign muons with large angular separation
- Each muon accompanied by a nearby opposite-sign track
- Muon-track systems reconstruct two $\mathrm{a_1}$-candidates

- Signal extracted with a binned max-likelihood fit to the 2D distribution of $(\mathrm{m}_{\mathrm{a}_1}^{(1)}, \mathrm{m}_{\mathrm{a}_1}^{(2)})$
- Background modelled in data with the use of CRs with modified isolation criteria applied to one or both muon-track systems

$(\mathrm{m}_{\mathrm{a}_1}^{(1)}, \mathrm{m}_{\mathrm{a}_1}^{(2)})$ bins



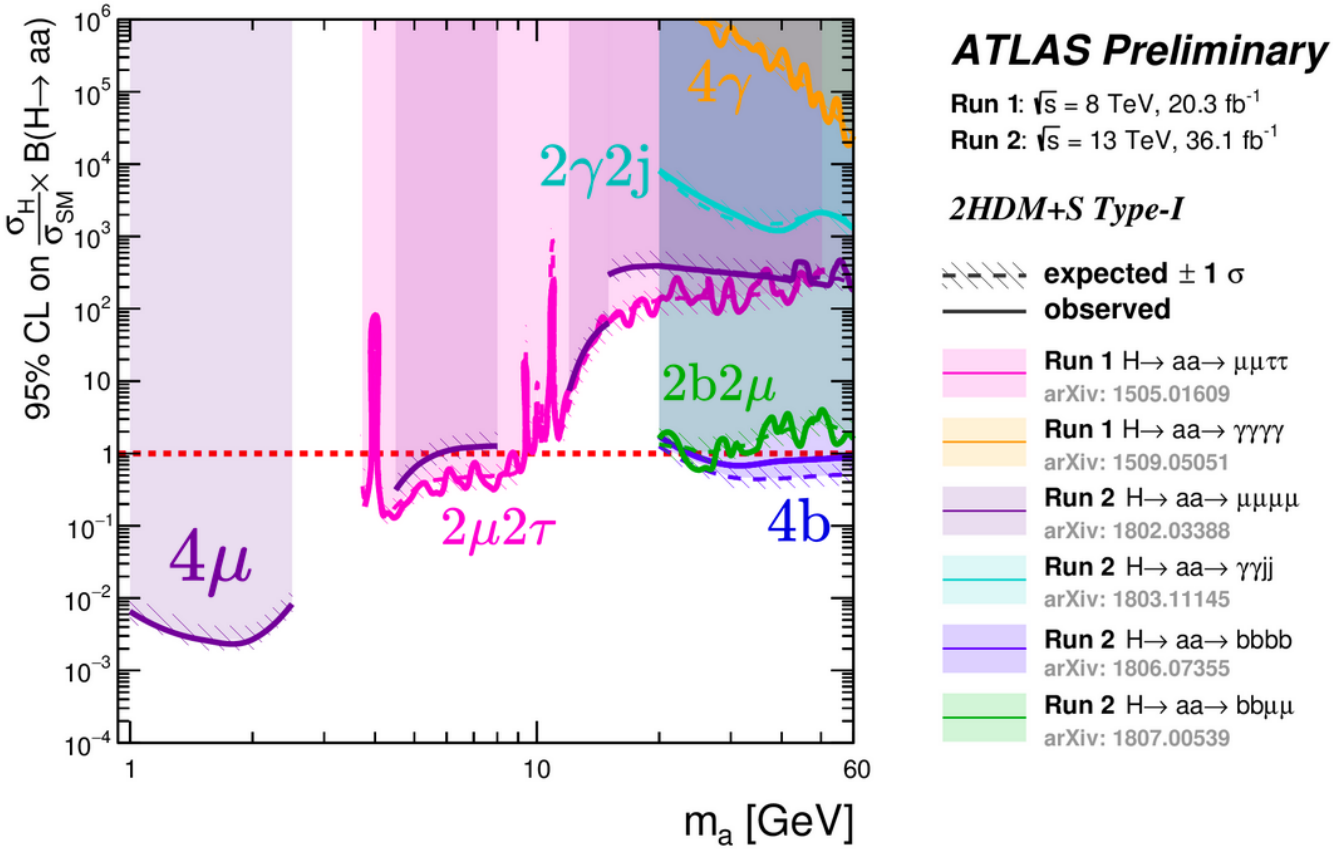
$\frac{\sigma_{\mathrm{H}}}{\sigma_{\mathrm{SM}}} \times \mathcal{B}(\mathrm{H} \to \mathrm{a_1 a_1})\mathcal{B}^2(\mathrm{a_1} \to \tau\tau)$



- Improved limits wrt. 8 TeV analysis (30% at low $\mathrm{m_{a_1}}$, 80% at intermediate $\mathrm{m_{a_1}}$ and new limits for up to 15 GeV)

$\mathrm{h}(125) \to \mathrm{a_1 a_1}$ *summary*

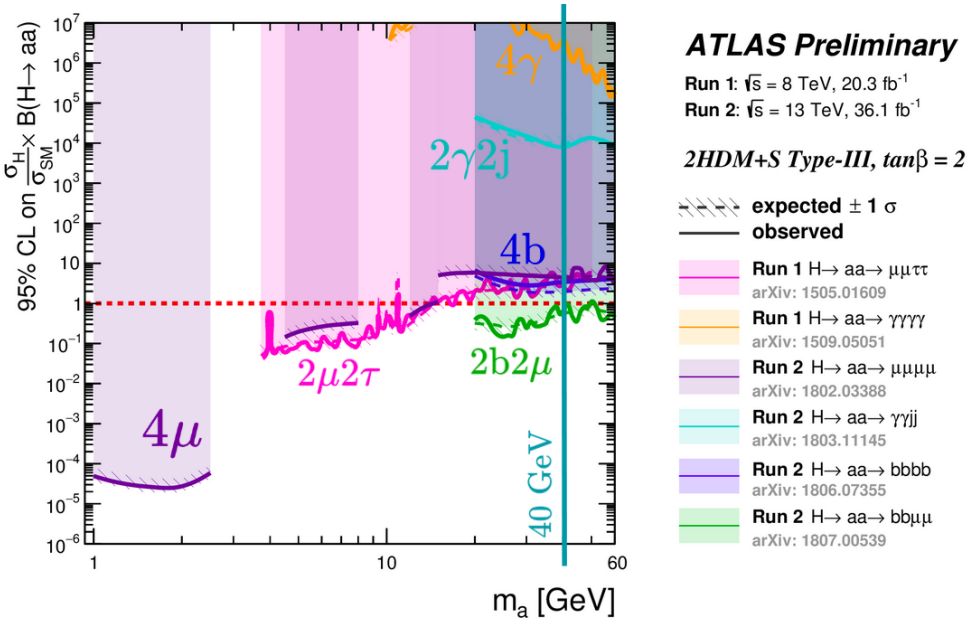
- Many analyses, in both ATLAS & CMS, searching for $\mathrm{h} \to \mathrm{a_1 a_1}$, most of them done with Run 2 data
- Observed and expected 95% CL upper limits on $\frac{\sigma_{\mathrm{H}}}{\sigma_{\mathrm{SM}}} \times \mathcal{B}(\mathrm{H} \to \mathrm{aa})$



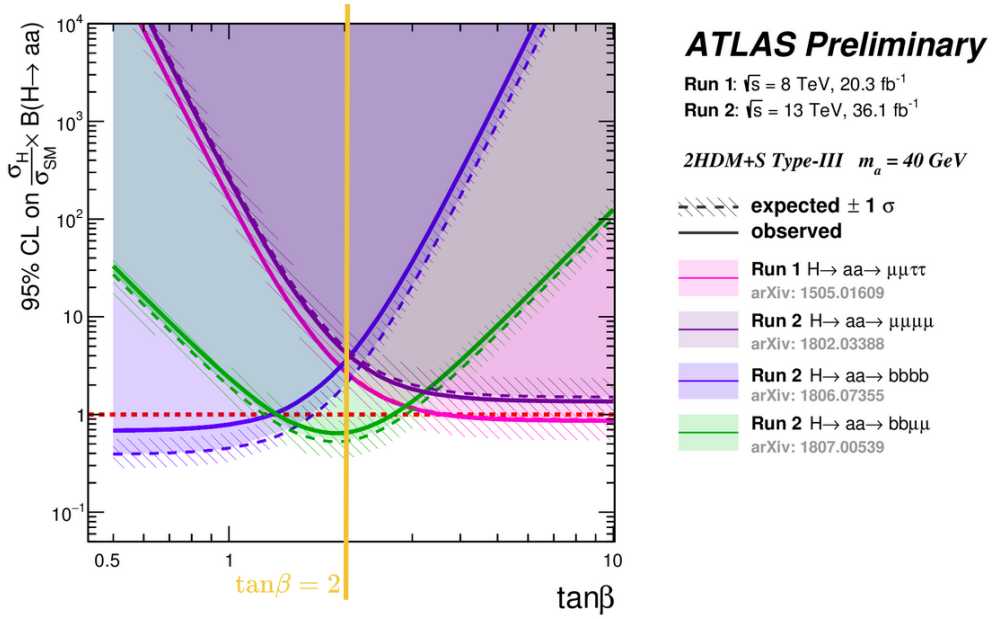
CMS $\mathrm{h} \to \mathrm{a_1 a_1}$ summary in backup

- Observed and expected 95% CL upper limits on $\frac{\sigma_H}{\sigma_{SM}} \times \mathcal{B}(H \to aa)$ in the context of 2HDM+S Type-III scenario for $\tan\beta = 2$ (left) and $m_a = 40$ GeV (right)

2HDM+S Type-III, $\tan\beta = 2$

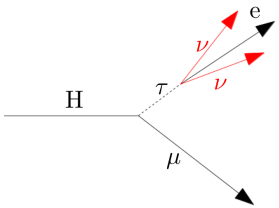


2HDM+S Type-III, $m_{a_1} = 40$ GeV

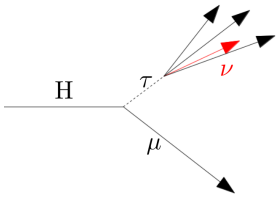


- Signal searched in events with a prompt μ/e, an oppositely charged τ-lepton and no b-jets

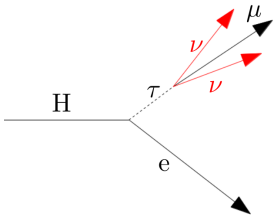
$\mathrm{H}^0 \to \mu\tau_\mathrm{e}$



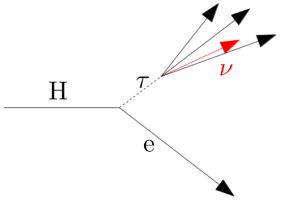
$\mathrm{H}^0 \to \mu\tau_\mathrm{h}$



$\mathrm{H}^0 \to \mathrm{e}\tau_\mu$

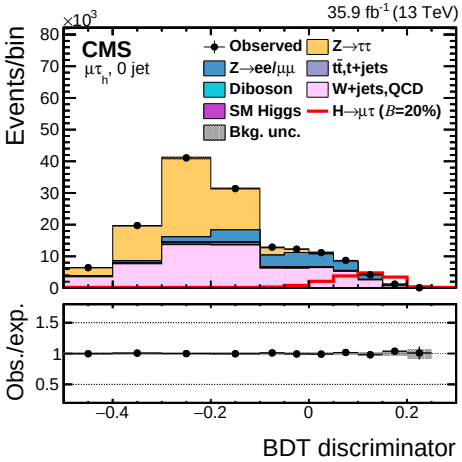


$\mathrm{H}^0 \to \mathrm{e}\tau_\mathrm{h}$

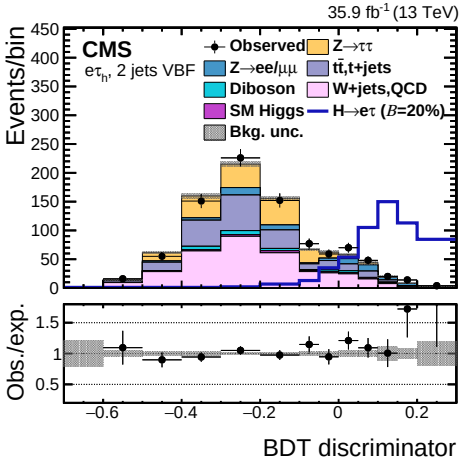


- 4 categories per channel based on number of jets (to enhance VBF and ggF)
- Boosted decision trees (BDT) approach to distinguish signal from background
- Background $\mathrm{Z} \to \tau\tau$ (QCD multijet) estimated from simulation (data)
- Joint fit to BDT discriminator to derive observed and expected limits

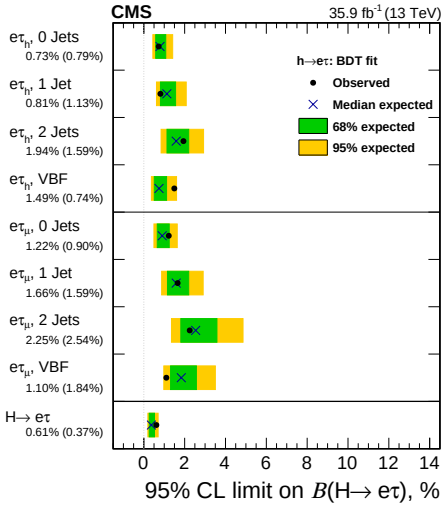
$\mathrm{H} \to \mu\tau_\mathrm{h}$, 0 jets



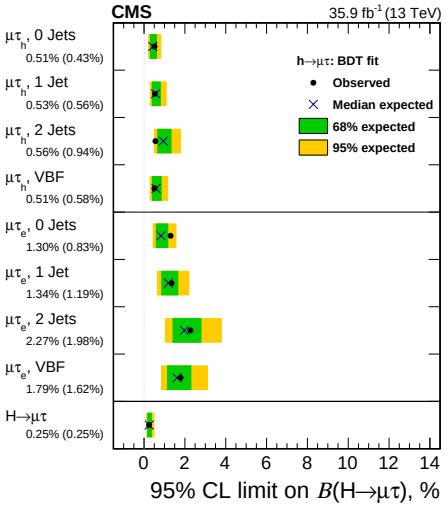
$\mathrm{H} \to \mathrm{e}\tau_\mathrm{h}$, 2 jets VBF



$\mathcal{B}(\mathrm{H} \to \mathrm{e}\tau)$

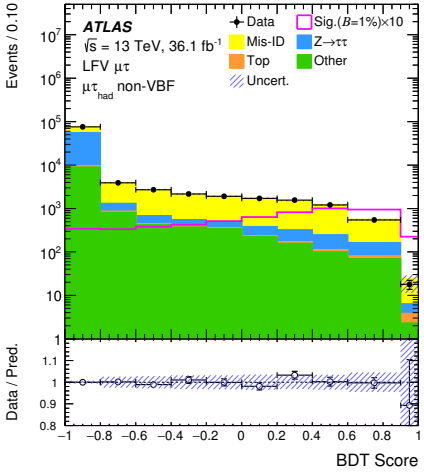


$\mathcal{B}(\mathrm{H} \to \mu\tau)$

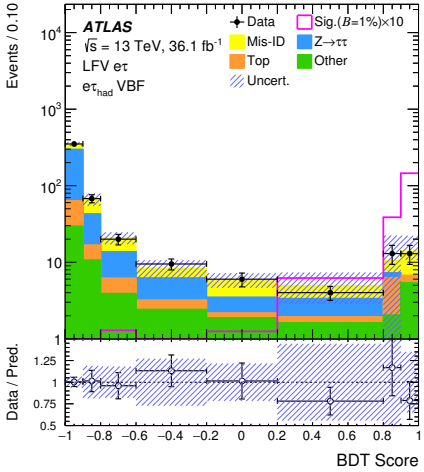


- Baseline selection similar to CMS, optimised in each channel for maximum $\mathrm{S/B}$
- 2 categories for each channel ($\mu\tau_\mathrm{e}$, $\mu\tau_\mathrm{h}$, $\mathrm{e}\tau_\mu$ and $\mathrm{e}\tau_\mathrm{h}$): VBF & non-VBF
- BDT variables selection optimised for each channel and category
- CRs, defined by inverting the b-jet veto (top-quark CR) and leading lepton p_T ($\mathrm{Z} \to \tau\tau$ CR) requirements, used to constrain the background normalization
- Events with misidentified objects ($\mathrm{jets} \to \ell$, $\mathrm{jets} \to \tau$, $\mathrm{e} \to \tau$) estimated with data-driven techniques

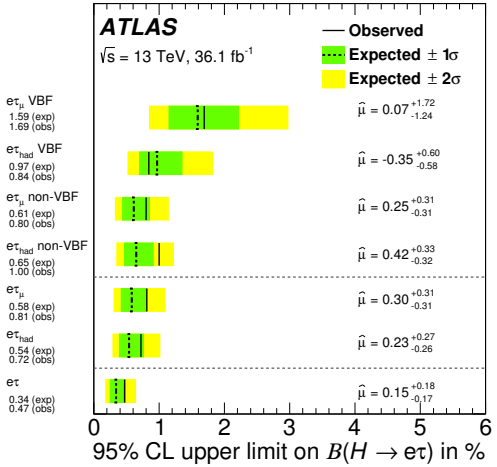
$\mathrm{H} \to \mu\tau_\mathrm{h}$ non-VBF



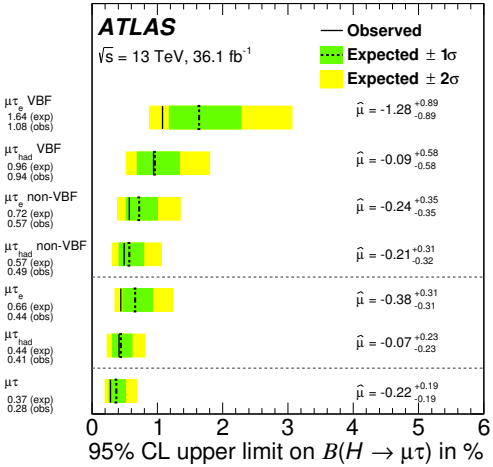
$\mathrm{H} \to \mathrm{e}\tau_\mathrm{h}$ VBF



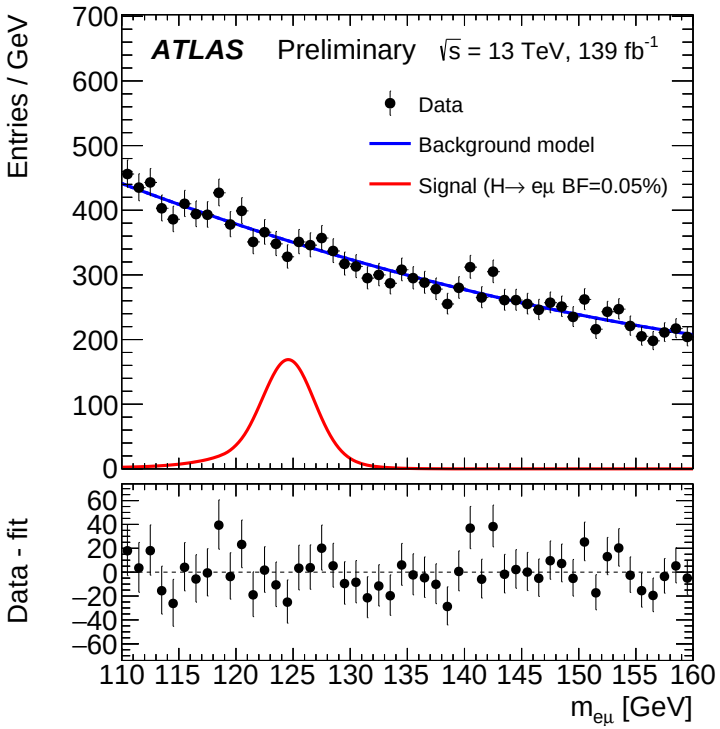
$\mathcal{B}(\mathrm{H} \to \mathrm{e}\tau)$

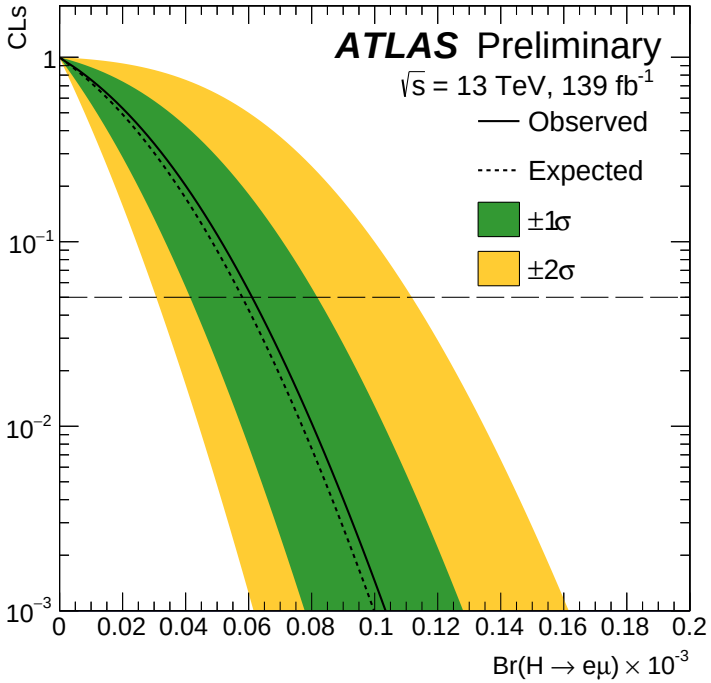


$\mathcal{B}(\mathrm{H} \to \mu\tau)$



- Strongly constrained by the indirect $\mu \to \mathrm{e}\gamma$ limit, $\mathcal{B}(\mathrm{H} \to \mathrm{e}\mu) < \mathcal{O}(10^{-9})$
- ✓ Full Run II data, 139 fb^{-1}
- Signal searched in events with two opposite charge leptons, no b-jets and low $\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$
- Background is top-quark & diboson production, W+jets, multijet events with jets misidentified as leptons
- 7 ggF categories based on leptons p_{T} & η, 1 VBF category based on number of jets
- Background measured with analytical functions constrained by the signal sidebands
- ✓ 95% CL upper limits on $\mathcal{B}(\mathrm{H} \to \mathrm{e}\mu)$ improved by a factor of 6 wrt previous results





LFV HIGGS DECAYS *Yukawa couplings*

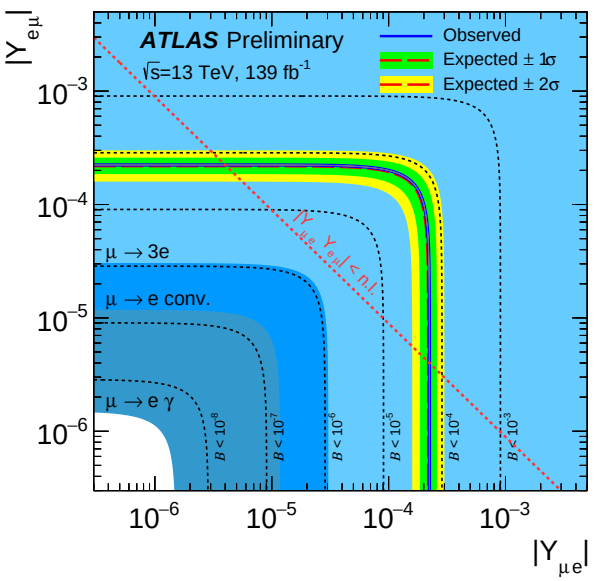
- Significant improvement on 95% CL upper limits with respect to Run I
- $\mathcal{B}(\mathrm{H} \to \mathrm{LFV})$ constraints can be interpreted in terms of LFV Yukawa couplings:

	$\mathcal{B}(\mathrm{H} \to \mu\tau)$	$\mathcal{B}(\mathrm{H} \to \tau\mathrm{e})$	$\mathcal{B}(\mathrm{H} \to \mathrm{e}\mu)$
ATLAS	$< 0.28\%$	$< 0.47\%$	$< 0.0061\%$
CMS	$< 0.25\%$	$< 0.61\%$	$< 0.035\ \%$ (8 TeV)

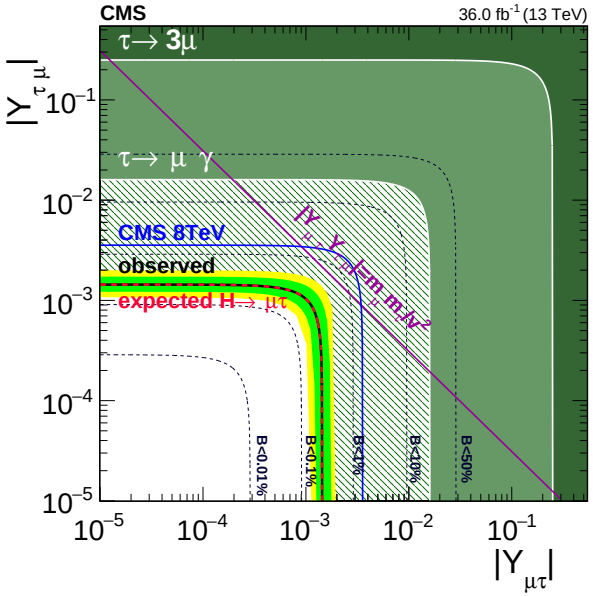
$$\Gamma(\mathrm{H} \to \ell^\alpha \ell^\beta) = \frac{\mathrm{m_H}}{8\pi}(|Y_{\ell^\beta \ell^\alpha}|^2 + |Y_{\ell^\alpha \ell^\beta}|^2),$$

$$\mathcal{B}(\mathrm{H} \to \ell^\alpha \ell^\beta) = \frac{\Gamma(\mathrm{H} \to \ell^\alpha \ell^\beta)}{\Gamma(\mathrm{H} \to \ell^\alpha \ell^\beta) + \Gamma_{\mathrm{SM}}}$$

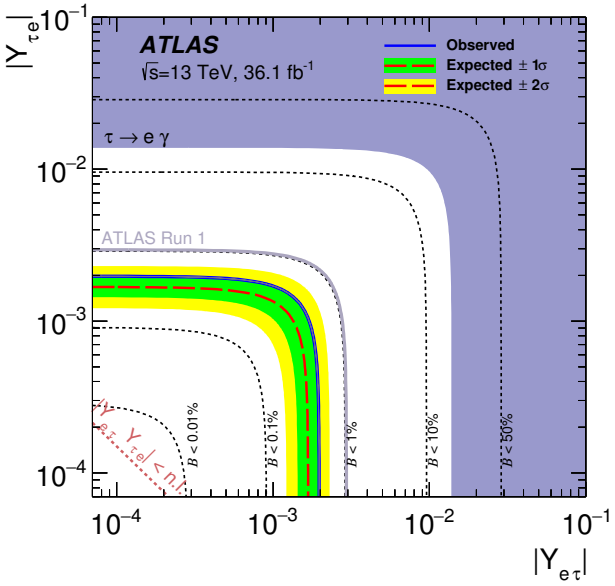
$\mathrm{H} \to \mathrm{e}\mu$



$\mathrm{H} \to \mu\tau$



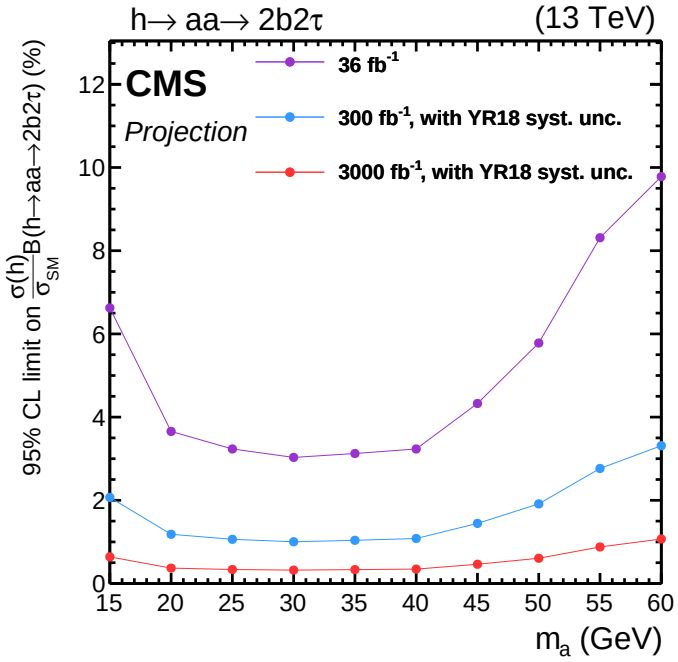
$\mathrm{H} \to \mathrm{e}\tau$

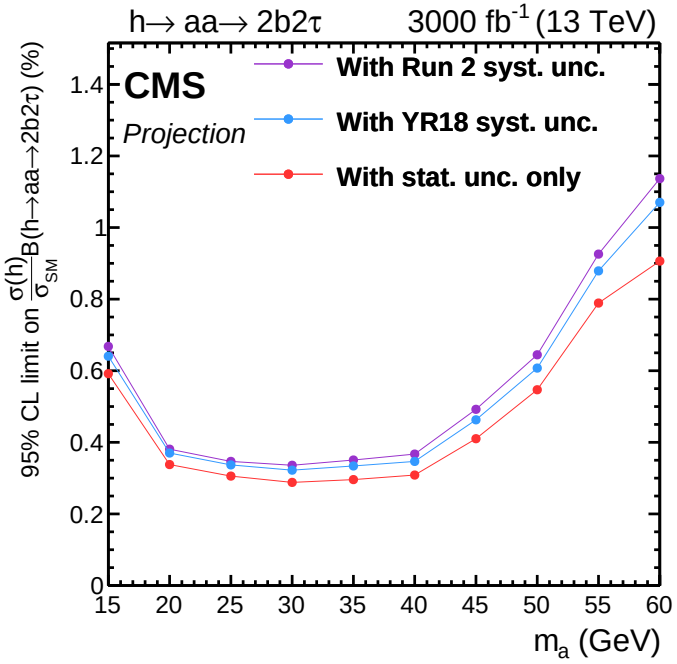


FUTURE PROSPECTS

High-Lumi LHC

- Run 2 analysis $\mathrm{h} \to \alpha\alpha \to \tau\tau\mathrm{bb}$ projected to `HL-LHC` conditions
- Extrapolations done under similar level of detector and triggering performance assumption
- 3 scenarios for the extrapolation of systematic uncertainties:
  1. Statistical-only: all systematic uncertainties are neglected
  2. Run-2: experimental & theoretical unc. same as in Run-2
  3. YR18: theoretical unc. devided by two, experimental unc. scale inversely with the square root of integrated luminosity with some lower limit





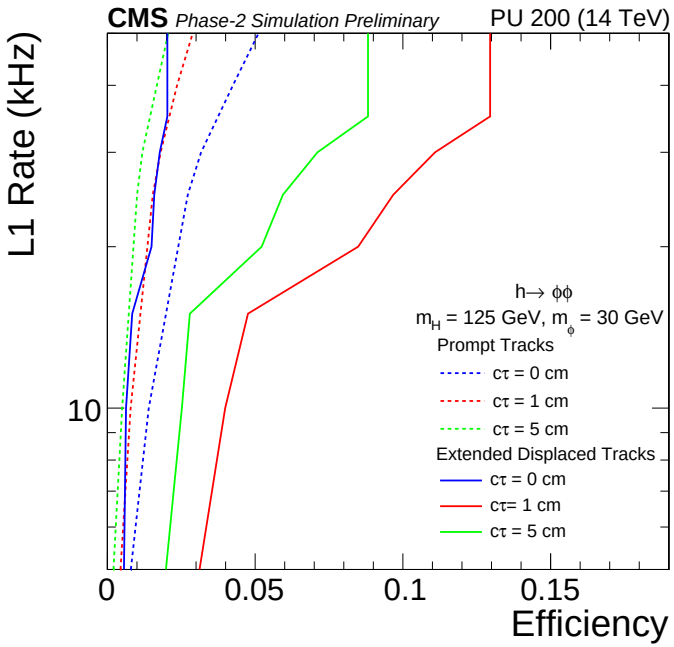
- Current trigger bandwidth major handle for BSM analyses
- CMS Phase-2 Tracker upgrade enables tracking information at Level-1 trigger (L1T)
  - ✓ Handles for rate suppression & lower thresholds → new phase space for BSM signals

$\mathrm{h}(125) \to \phi\phi \to 4j$

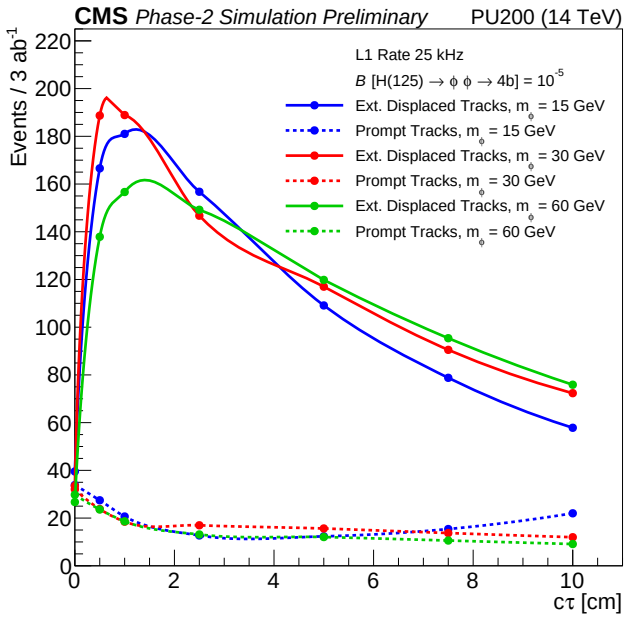
- ✓ Negligible SM background when ϕ has a macroscopic decay length
- ✗ Run 2: Majority of such events rejected at L1T due to low $\mathrm{H_T}$ thresholds

- New jet clustering algorithm utilises L1 tracking info to reconstruct tracks with impact parameter as large as 5 cm

Track jet $\mathrm{H_T}$ trigger



$\mathcal{B}(\mathrm{h}(125) \to \phi\phi \to 4\mathrm{j}) = 10^{-5}$



SUMMARY

- ATLAS & CMS working on a broad program of exotic Higgs boson decays searches covering a large variety of 2HDM models
- No significant excess above the SM background found so far
- Limits becoming more stringent with partial or full Run 2 dataset
- More results to come with the full Run 2 dataset!

- Future looks promising as $\mathrm{HL-LHC}$ opens new phase space for BSM searches

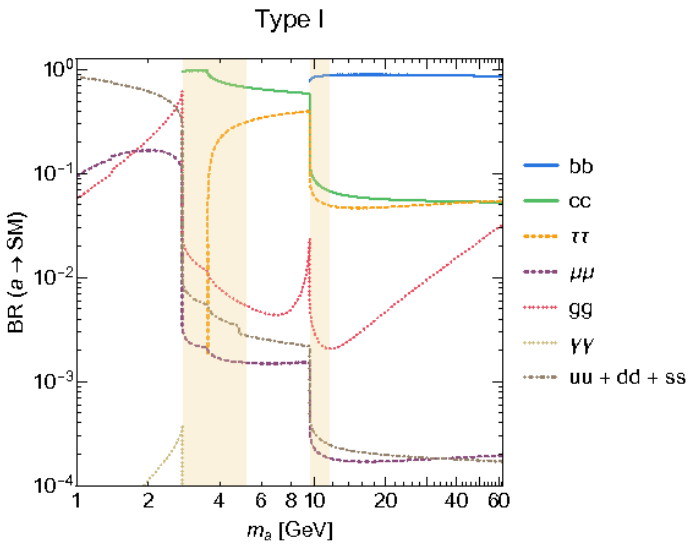
Thank you for your attention!

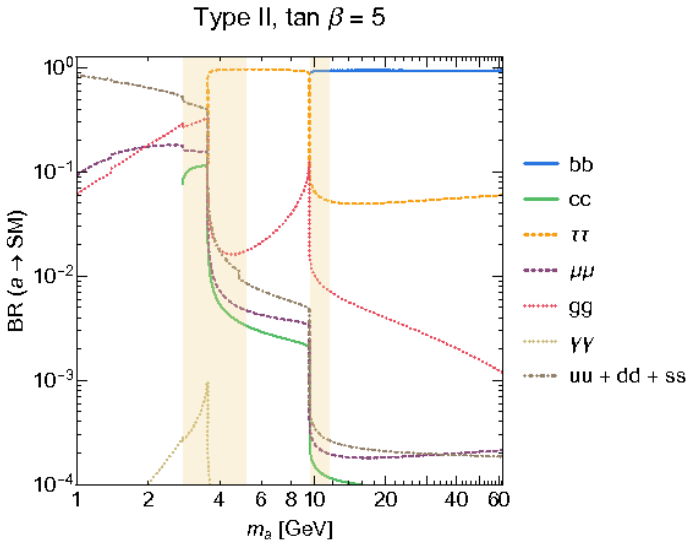
BACKUP

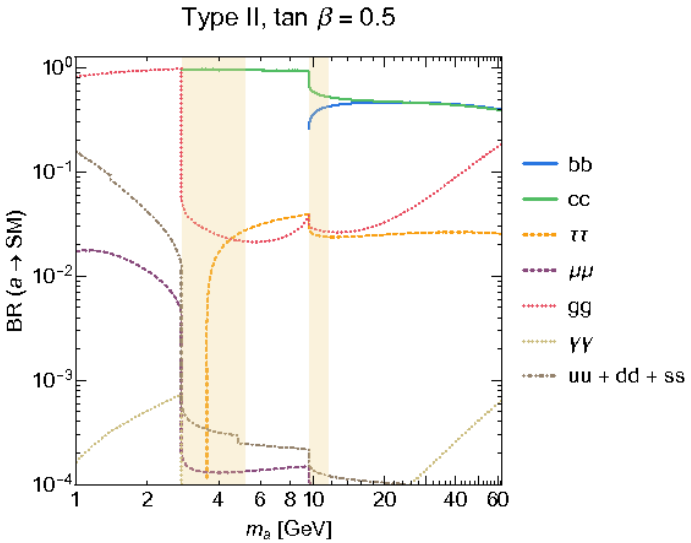
BACKUP *Navigation*

- Branching fractions (page 22)
- CMS (page 24)
- ATLAS (page 29)
- Projections to HL-LHC (page 32)

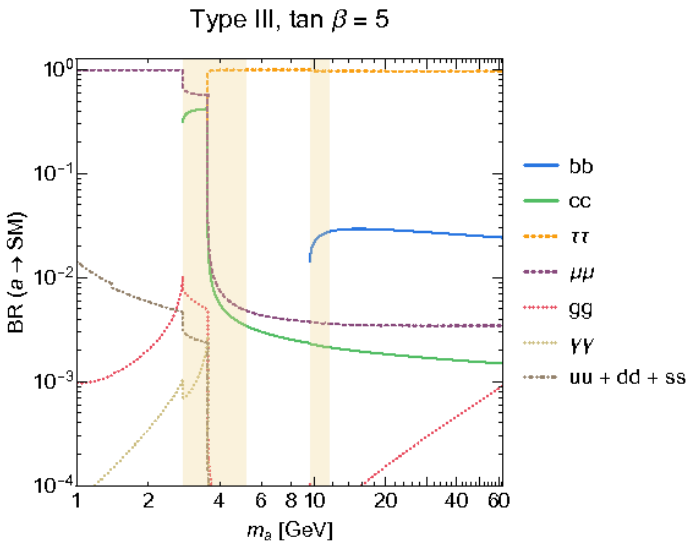
BACKUP *Branching fractions*

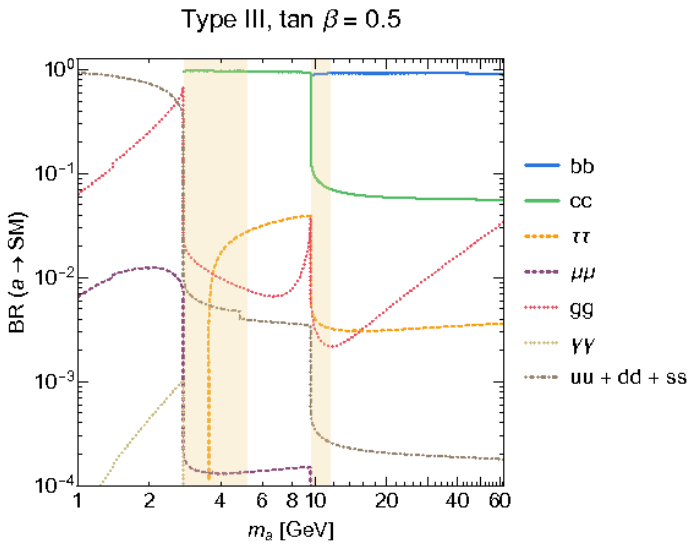


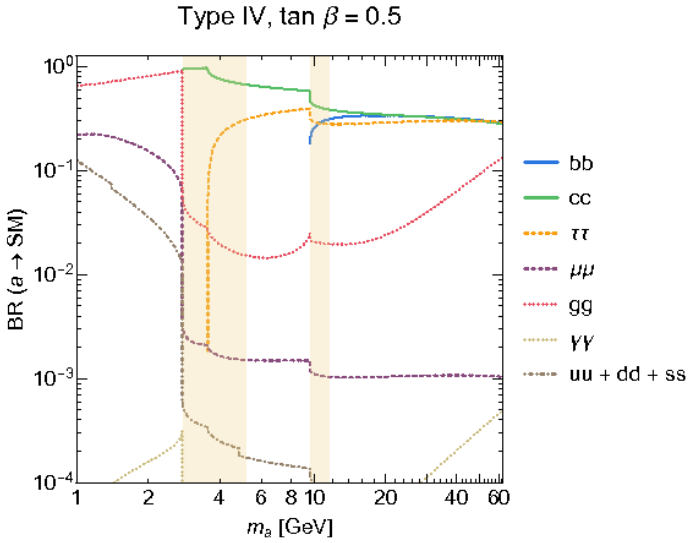


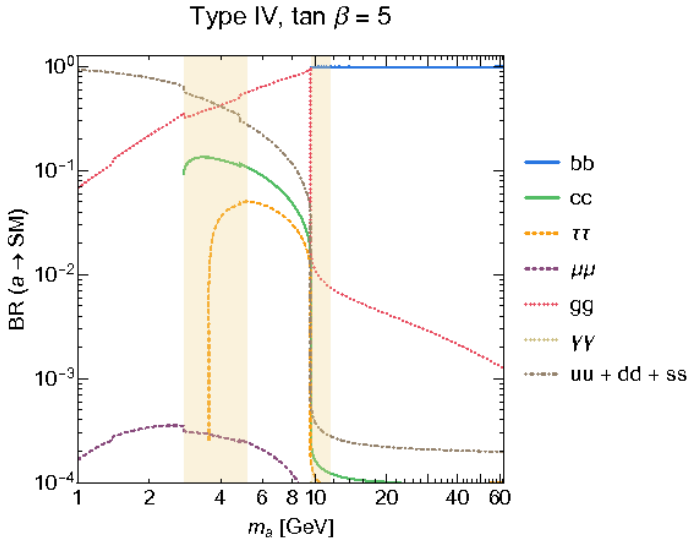


BACKUP *Branching fractions*



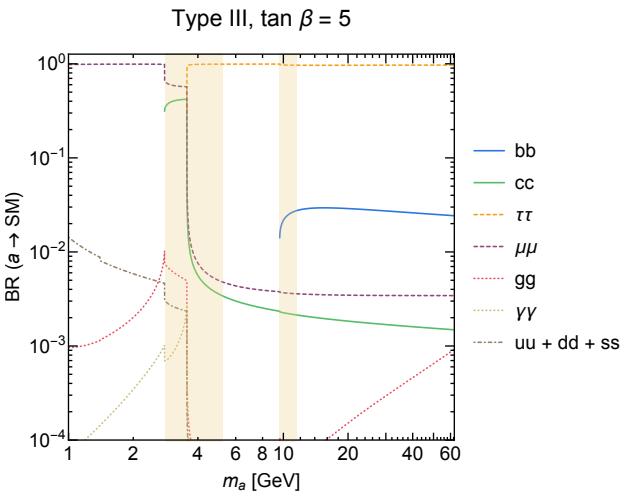




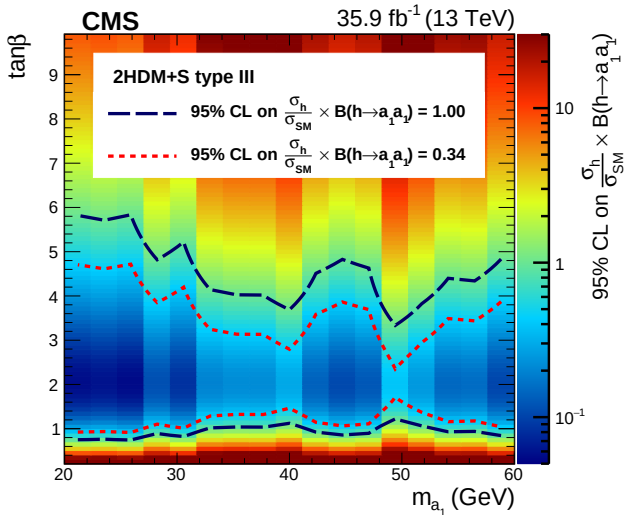


$\mathrm{h} \to \mathrm{a_1 a_1} \to \mathrm{bb}\mu\mu$

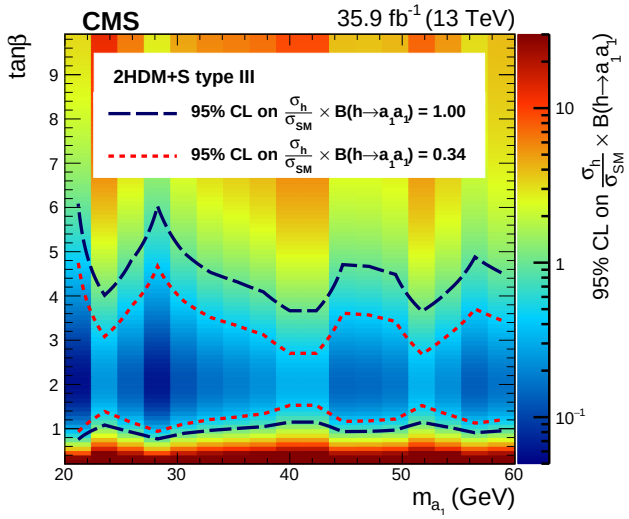
- Overlap between $\mathrm{h} \to \mathrm{a_1 a_1} \to \mathrm{bb}\mu\mu$ and $\mathrm{h} \to \mathrm{a_1 a_1} \to \tau\tau\mu\mu$ final states is checked in Type-III 2HDM+S model, including $\mu\mu\tau\tau$ signal that is misidentified as $\mu\mu\mathrm{bb}$



without $\mu\mu\tau\tau$



with $\mu\mu\tau\tau$



- Contribution from $\mu\mu\tau\tau$ non-negligible

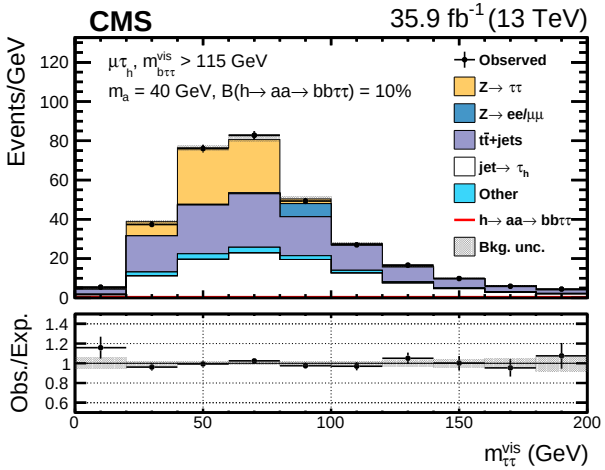
Phys. Lett. B 795 (2019) 398
arXiv:1812.06359

$\mathrm{h} \to \mathrm{a_1 a_1} \to \tau\tau bb$

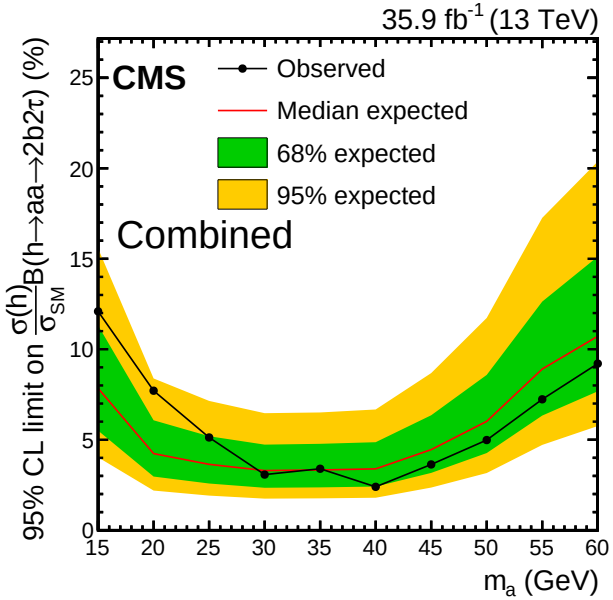
Phys. Lett. B 785 (2018) 462

- $15 < \mathrm{m_{a_1}} < 60$ GeV
- 3 final states considered: $\tau_\mathrm{e}\tau_\mu\mathrm{bb}$, $\mathrm{e}\tau_\mathrm{h}\mathrm{bb}$, & $\mu\tau_\mathrm{h}\mathrm{bb}$ (most sensitive)
- 4 categories per final state, based on $\mathrm{m}^{\mathrm{vis}}_{\mathrm{b}\tau\tau}$
- Background $\mathrm{t\bar{t}}$, W+jets (estimated from simulation), jets misidentified as τ_h (from data)
- Signal extracted from binned maximum-likelihood fit to the $\mathrm{m}^{\mathrm{vis}}_{\tau\tau}$ distribution

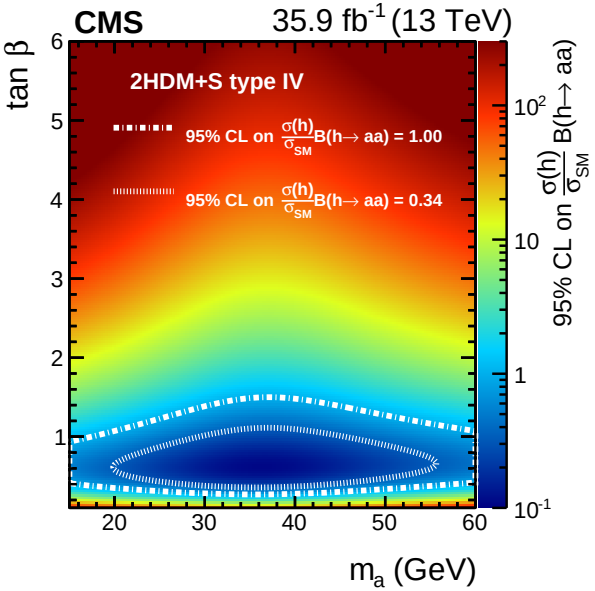
$\mu\tau_\mathrm{h}\mathrm{bb}$ final state, $\mathrm{m}^{\mathrm{vis}}_{\tau\tau}$



$\frac{\sigma_\mathrm{h}}{\sigma_\mathrm{SM}} \times \mathcal{B}(\mathrm{h} \to \mathrm{aa} \to 2\mathrm{b}2\tau)$



$\frac{\sigma_\mathrm{h}}{\sigma_\mathrm{SM}} \times \mathcal{B}(\mathrm{h} \to \mathrm{aa})$



$\mathcal{B}(\mathrm{h} \to \mathrm{a_1 a_1} \to 2\mathrm{b}2\tau) < 3 - 12\%$ (Obs.)

$\mathrm{h} \to \mathrm{a_1 a_1} \to \mu\mu\tau\tau$

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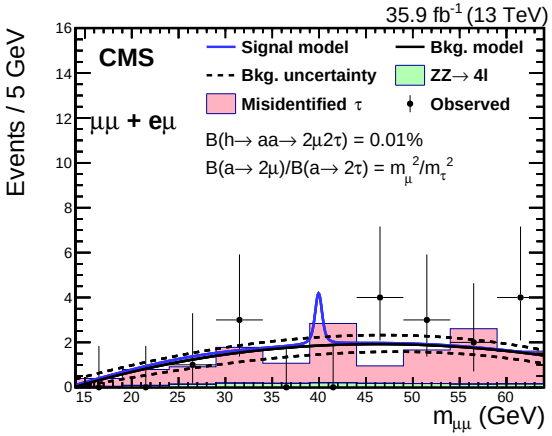
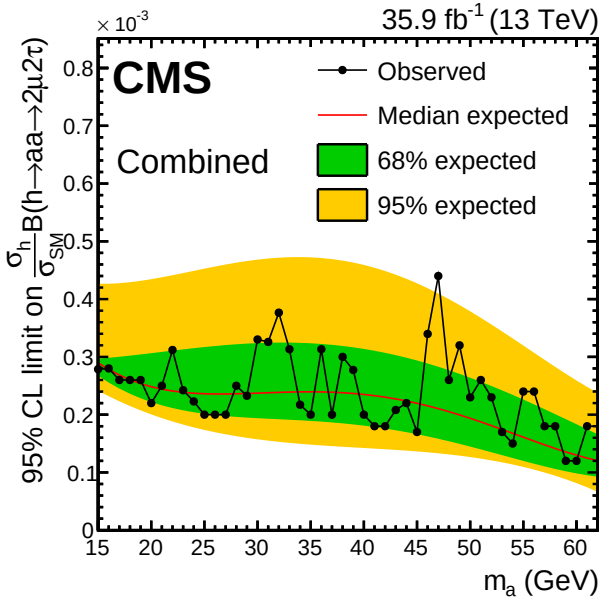
- $15 < \mathrm{m_{a_1}} < 62.5$ GeV
- 4 final states considered: $\mu\mu e\mu$, $\mu\mu e\tau_\mathrm{h}$, $\mu\mu\mu\tau_\mathrm{h}$ and $\mu\mu\tau_\mathrm{h}\tau_\mathrm{h}$
- Background Z pair production (jets misidentified as leptons) estimated in simulation (data)
- Signal extracted from maximum-likelihood fit to the $\mathrm{m}_{\mu\mu}$ distribution
- Improved limits wrt previous results by a factor of 2 or more in all types of 2HDM+S

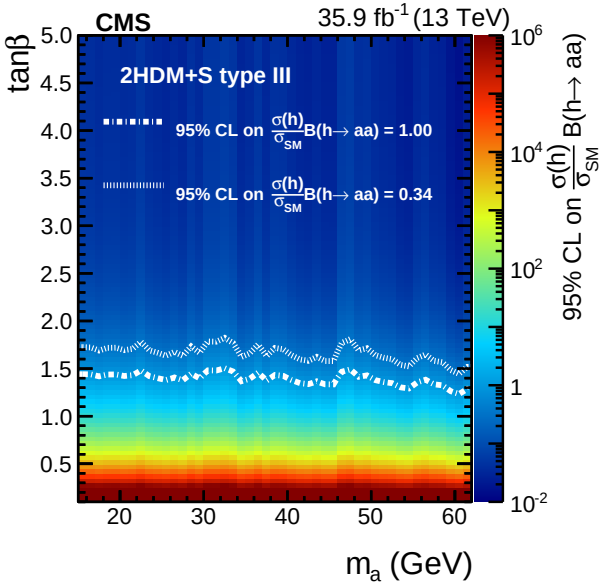
$\mathrm{m}_{\mu\mu}$ in $\mu\mu e\mu$ category



$\frac{\sigma_\mathrm{h}}{\sigma_\mathrm{SM}} \times \mathcal{B}(\mathrm{h} \to \mathrm{aa} \to 2\mu 2\tau)$



$\frac{\sigma_\mathrm{h}}{\sigma_\mathrm{SM}} \times \mathcal{B}(\mathrm{h} \to \mathrm{aa})$

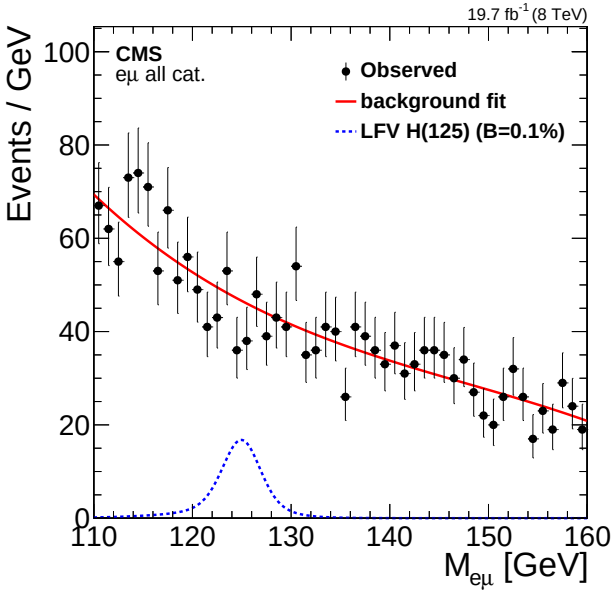


LFV $\mathrm{H} \to \mathrm{e}\gamma$

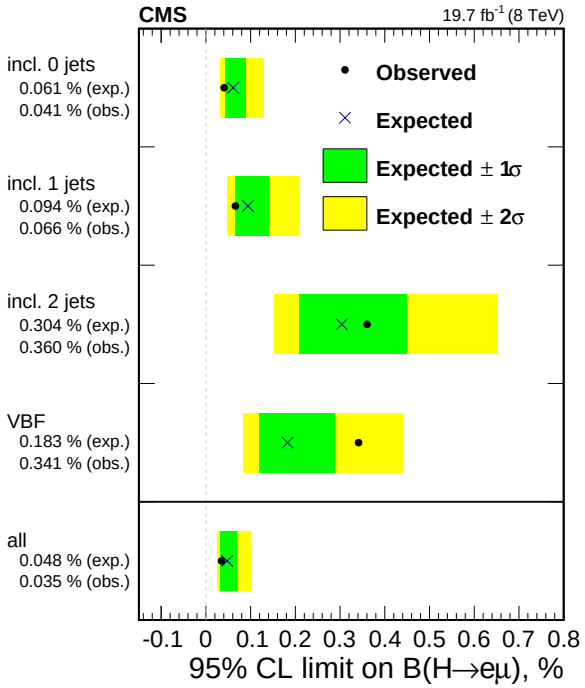
Phys. Lett. B 763C (2016) 472

- Signal searched in events with two isolated leptons, up to 2 jets, low $\mathrm{E_T^{miss}}$ & no b-jets
- Considering ggF and VBF Higgs production mechanisms
- 9 ggF and 2 VBF categories based on leptons detection area & number of jets
- Background originates from $\mathrm{Z} \to \tau\tau$, $\mathrm{t\bar{t}}$, jets misidentified as leptons
- Signal extracted from fit to the $\mathrm{M_{e\mu}}$ distribution in the range 110 GeV $< \mathrm{M_{e\mu}} <$ 160 GeV

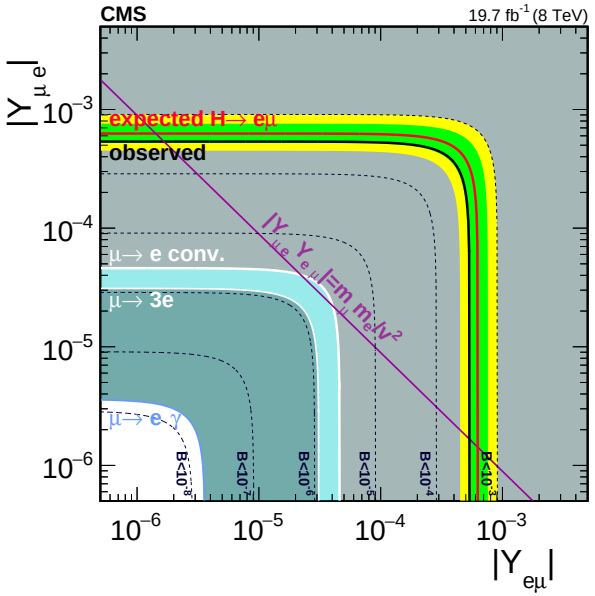
$\mathrm{M_{e\mu}}$, inclusive



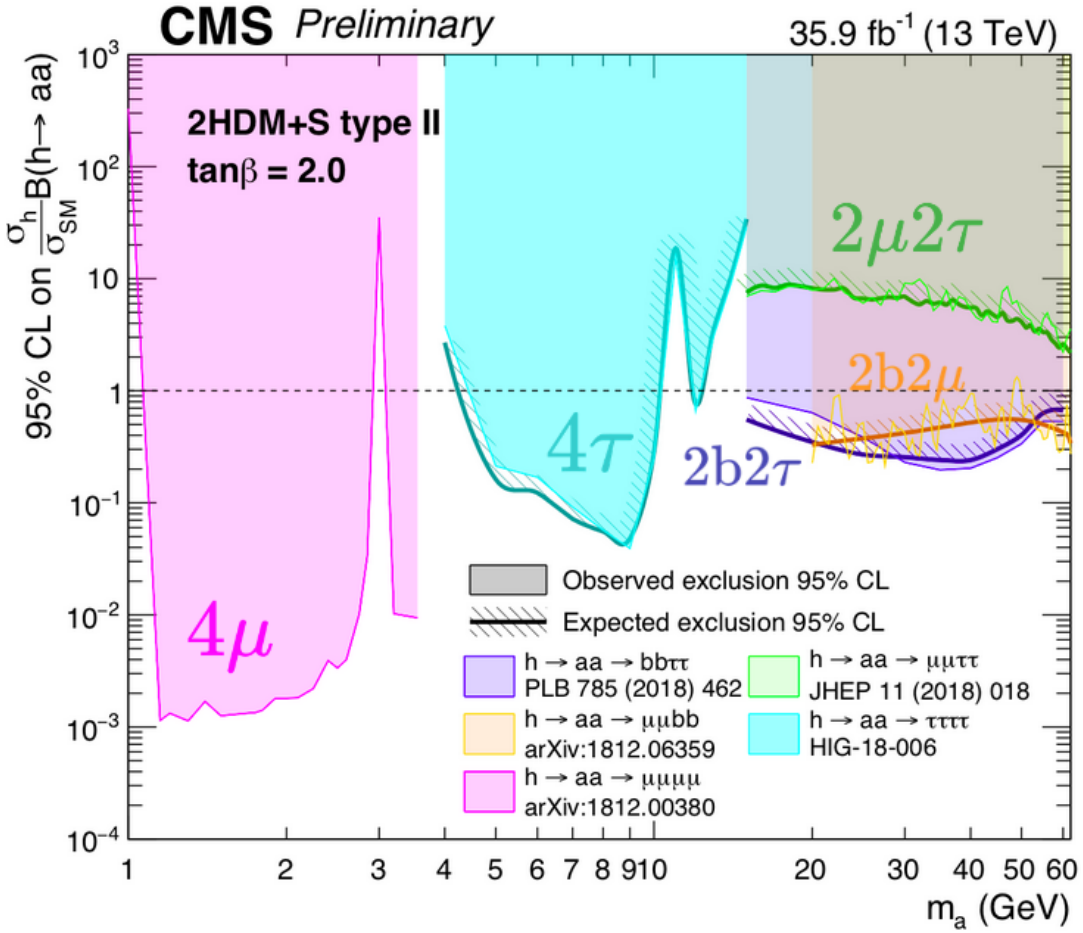
$\mathcal{B}(\mathrm{H} \to \mathrm{e}\mu) < 0.035\%$



$\sqrt{|\mathrm{Y_{e\mu}}|^2 + |\mathrm{Y_{\mu e}}|^2} < 5.4 \times 10^{-4}$



- Observed and expected 95% CL upper limits on $\frac{\sigma_{\mathrm{H}}}{\sigma_{\mathrm{SM}}} \times \mathcal{B}(\mathrm{H} \to \mathrm{aa})$ in the context of 2HDM+S Type-II with $\tan\beta = 2$



$\mathrm{H} \to \mathrm{ZX} \to 4\ell$ & $\mathrm{H} \to \mathrm{XX} \to 4\ell$ $(\mathrm{X} = \mathrm{a}, \mathrm{Z_d})$

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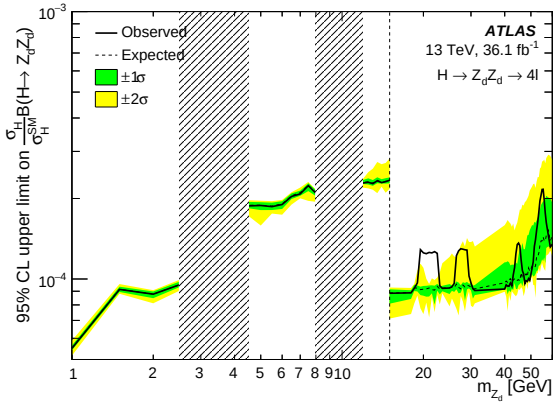
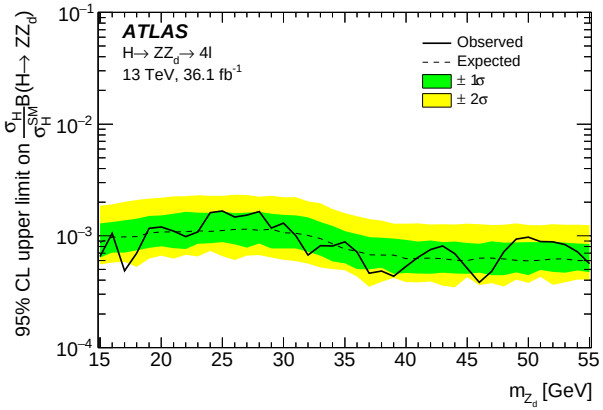
- Final states considered:
  $15 < \mathrm{m_X} < 60$ GeV: 4e, 2e2μ, 4μ
  $1 < \mathrm{m_X} < 15$ GeV: 4μ
- Benchmarks considered:
  1. Extended SM with a dark-sector, $\mathrm{U(1)_d}$ (produces vector boson $\mathrm{Z_d}$)
  2. 2HDM with an additional singlet scalar field, 2HDM+S (produces pseudoscalar a)
- Same-flavour opposite sign (SFOS) leptons form quadruplets, $\mathrm{m}_{4\ell}$ consistent with $\mathrm{m_H}$
- Main background: $\mathrm{H} \to \mathrm{ZZ}^* \to 4\ell$, $\mathrm{ZZ}^* \to 4\ell$, triboson, jets misidentified as leptons
- Background estimated using simulation & data-driven techniques

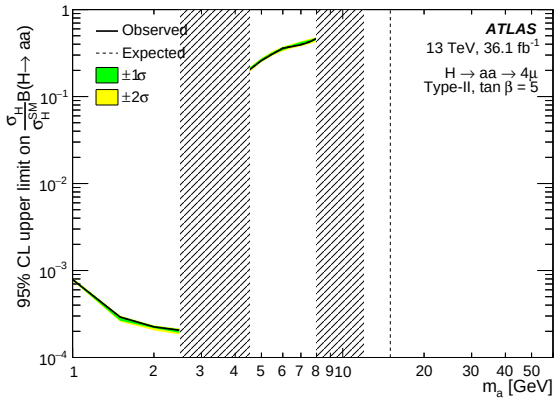
$\frac{\sigma_{\mathrm{H}}}{\sigma_{\mathrm{SM}}} \mathcal{B}(\mathrm{H} \to \mathrm{Z_d Z_d})$



$\frac{\sigma_{\mathrm{H}}}{\sigma_{\mathrm{SM}}} \mathcal{B}(\mathrm{H} \to \mathrm{ZZ_d})$



$\frac{\sigma_{\mathrm{H}}}{\sigma_{\mathrm{SM}}} \mathcal{B}(\mathrm{H} \to \mathrm{aa})$



$\mathrm{VH} \to \mathrm{Vaa} \to (\ell\ell/\ell\nu)\mathrm{bbbb}$

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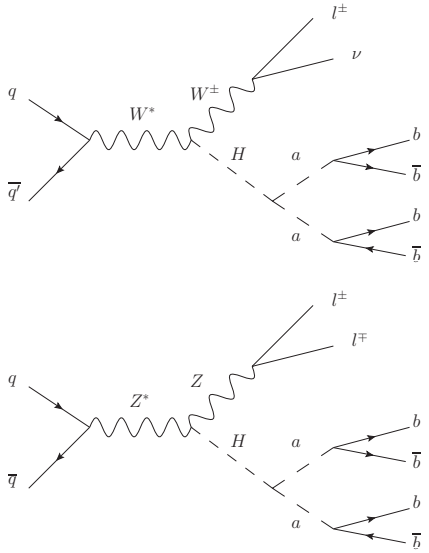
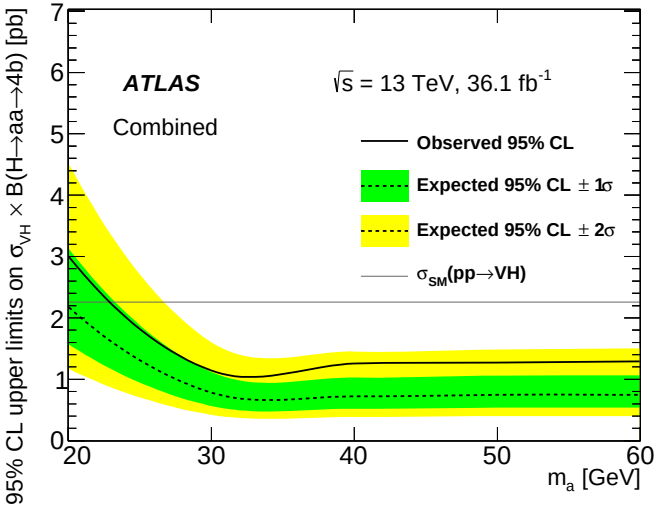
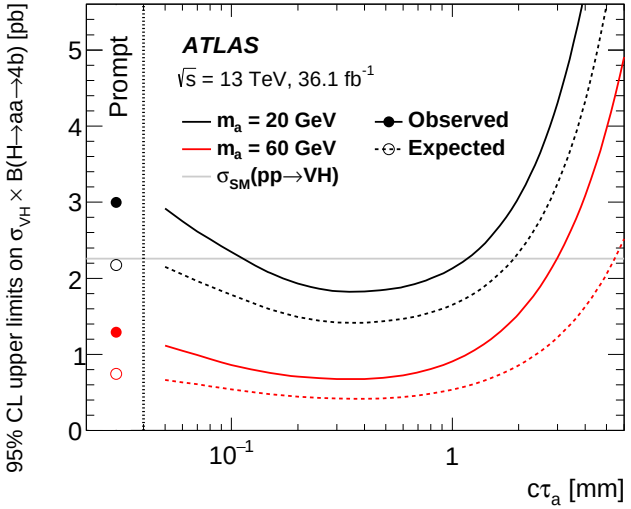
- $20 < \mathrm{m_a} < 60$ GeV
- b-quarks produced promptly or with $\mathrm{c}\tau_\mathrm{a}$ up to 6 mm
- Signal searched in events with $\geq\ 1\ \mu/\mathrm{e}, \geq\ 2\ \mathrm{b-jets}$
- Background: $\mathrm{t\bar{t}}$, W/Z+jets, diboson, jets misidentified as leptons
- CRs, defined based on number of leptons, jets & b-jets, used to constrain the background (using simulation & data)
- Boosted Decision Tree (BDT) approach to discriminate signal from background



Prompt, 3.0 - 1.3 pb



best limits for $\mathrm{c}\tau_\mathrm{a} \approx 0.4$ mm

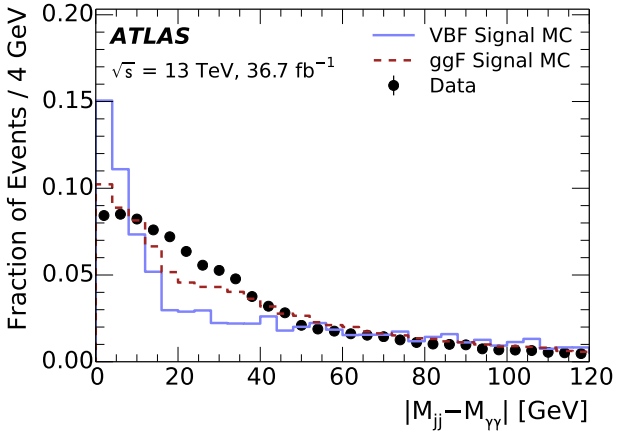


$\mathrm{h} \to \mathrm{aa} \to \gamma\gamma\mathrm{jj}$

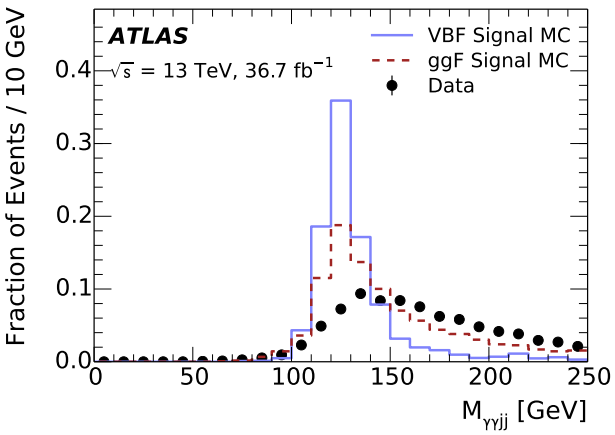
Phys. Lett. B 782 (2018) 750

- $20 < \mathrm{m}_{\mathrm{a}_1} < 60$ GeV
- First time search for $\mathrm{h} \to \mathrm{aa} \to \gamma\gamma\mathrm{jj}$
  - Important in models with suppressed fermionic decays
- Considering vector-boson fusion (VBF) Higgs production mechanism
- Signal is searched in events with 2 photons, ≥ 4 jets. Construct:
  - $\mathrm{m}_{\mathrm{jj}}^{\mathrm{VBF}} > 500$ GeV with VBF jets, m_{jj} with signal jets
  - $\mathrm{m}_{\gamma\gamma}$ gives 5 regimes: $|\mathrm{m}_{\mathrm{jj}} - \mathrm{m}_{\gamma\gamma}| > 12 - 24$ GeV
  - $100 < \mathrm{m}_{\gamma\gamma\mathrm{jj}} < 150$ GeV
- $\gamma\gamma + \mathrm{multi\ jet}$ background estimated from data using sidebands
- No significant excess is observed wrt predicted SM background

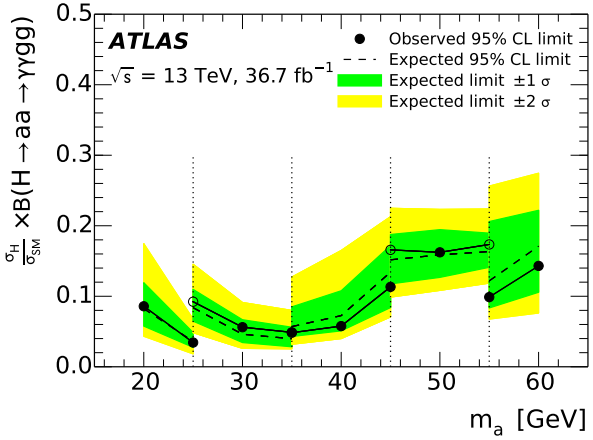
$|\mathrm{m}_{\mathrm{jj}} - \mathrm{m}_{\gamma\gamma}|$



$\mathrm{m}_{\gamma\gamma\mathrm{jj}}$



$\frac{\sigma_{\mathrm{h}}}{\sigma_{\mathrm{SM}}} \times \mathcal{B}(\mathrm{h} \to \mathrm{aa} \to \gamma\gamma\mathrm{gg})$



BACKUP *Projections to HL-LHC*

- Upper limits on $\mathcal{B}(\mathrm{h} \to \mathrm{aa} \to 2\tau 2\mathrm{b})$ interpreted to $\mathcal{B}(\mathrm{h} \to \mathrm{aa})$ limits in different 2HDM+S models assuming YR18 systematic uncertainties