Search for exotic decays of the Higgs boson into two light pseudoscalars in final states with muons and tau leptons

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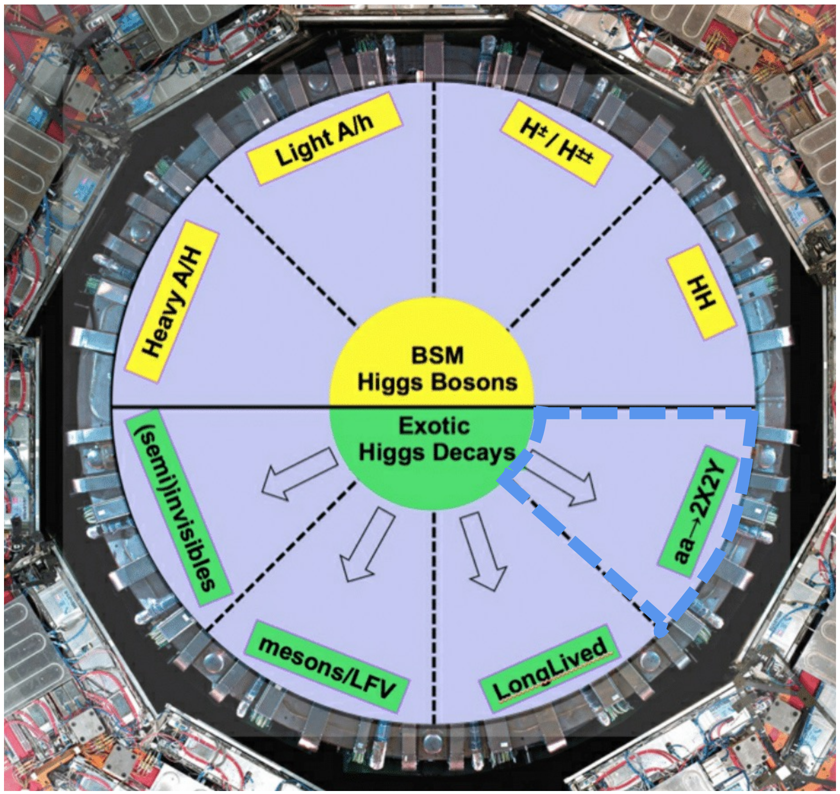
Introduction

> Discovery of the SM Higgs boson will be a decade old by next year!

How do we directly search for new physics in the Higgs sector?

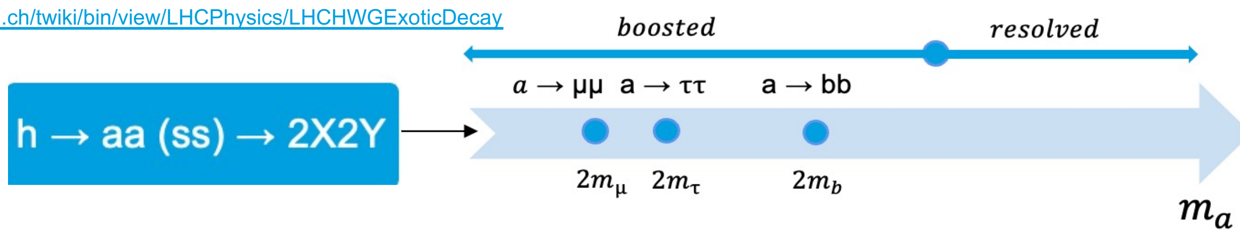


https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWGExoticDecay

Exotic higgs decays
natural signature of very broad class of beyond the SM theories

- 2 Higgs doublets
MSSM, 5 physical Higgs bosons:
$h_{1,2,3}$, H^+, H^-
(already strongly constrained by existing data)

- 2 Higgs doublets + 1 additional singlet (2HDM + 1S)
7 physical Higgs bosons:
$h_{1,2,3}$, H^+, H^-, $\boxed{a_{1,2}}$
under certain assumptions, phenomenology of $h \to aa \to x\bar{x}y\bar{y}$ decays determined by three independent parameters:
$B(h \to aa)$, $\tan\beta$, and m_a



Direct searches: Benchmark scenario 2HDM+1S

Higgs-fermion couplings:

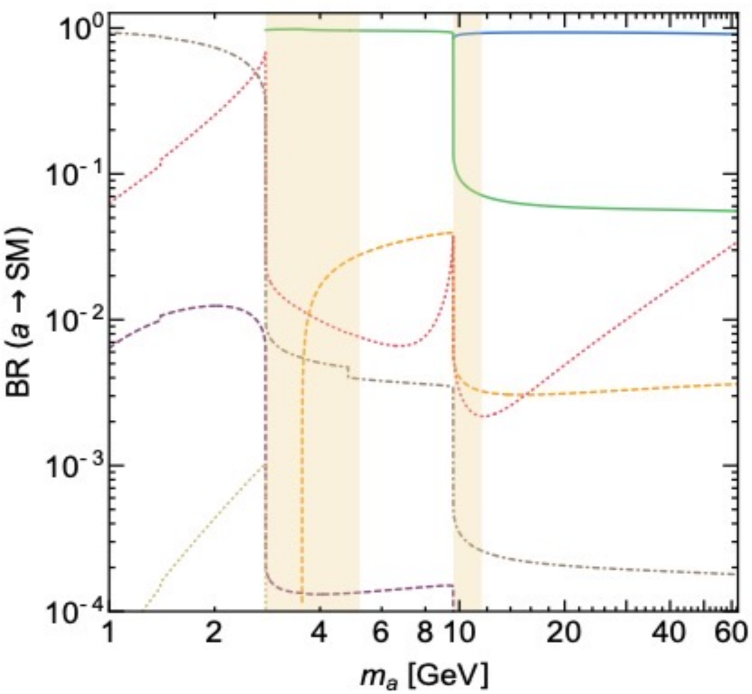
Model	2HDM I	2HDM II	2HDM III	2HDM IV
u	H_2	H_2	$\boxed{H_2}$	H_2
d	H_2	H_1	$\boxed{H_2}$	H_1
e	H_2	H_1	$\boxed{H_1}$	H_2

Type III: decays to ττ dominate over decays to $b\bar{b}$ above the $b\bar{b}$ threshold, with branching fraction to leptons increasing as a function of tanβ

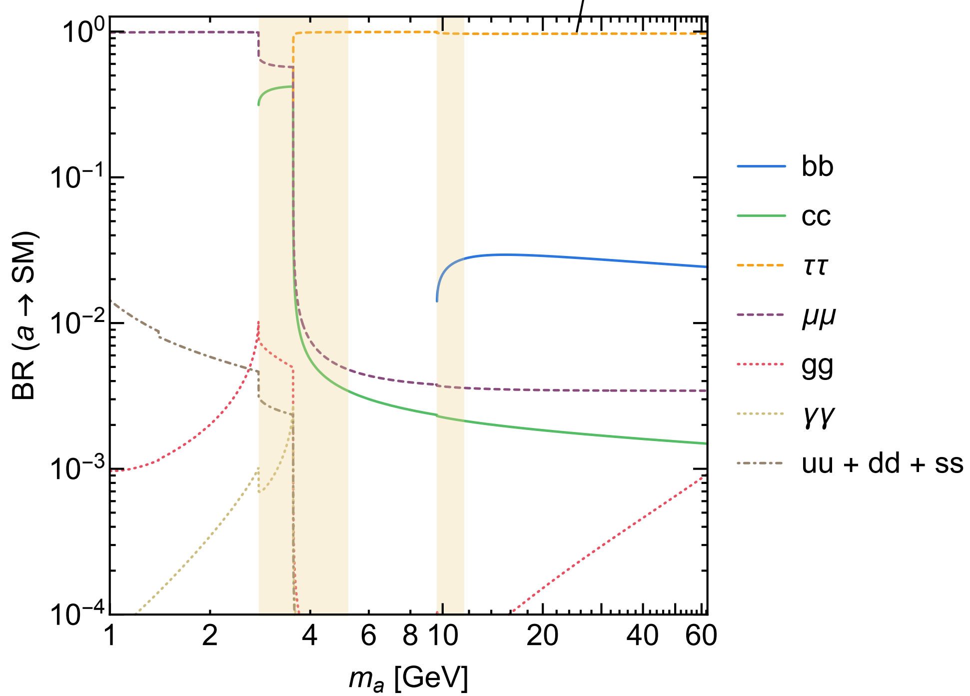
Why the interest in final states with leptons? 🤔

Type III, tan β =0.5

doi:10.1103/PhysRevD.90.075004



Type III, tan β = 5



Signal signature and analysis strategy

- probe low m_{a_1} region: $2m_\tau < m_{a_1} < 2m_b$ (highly boosted a_1 bosons → collimated decay products)

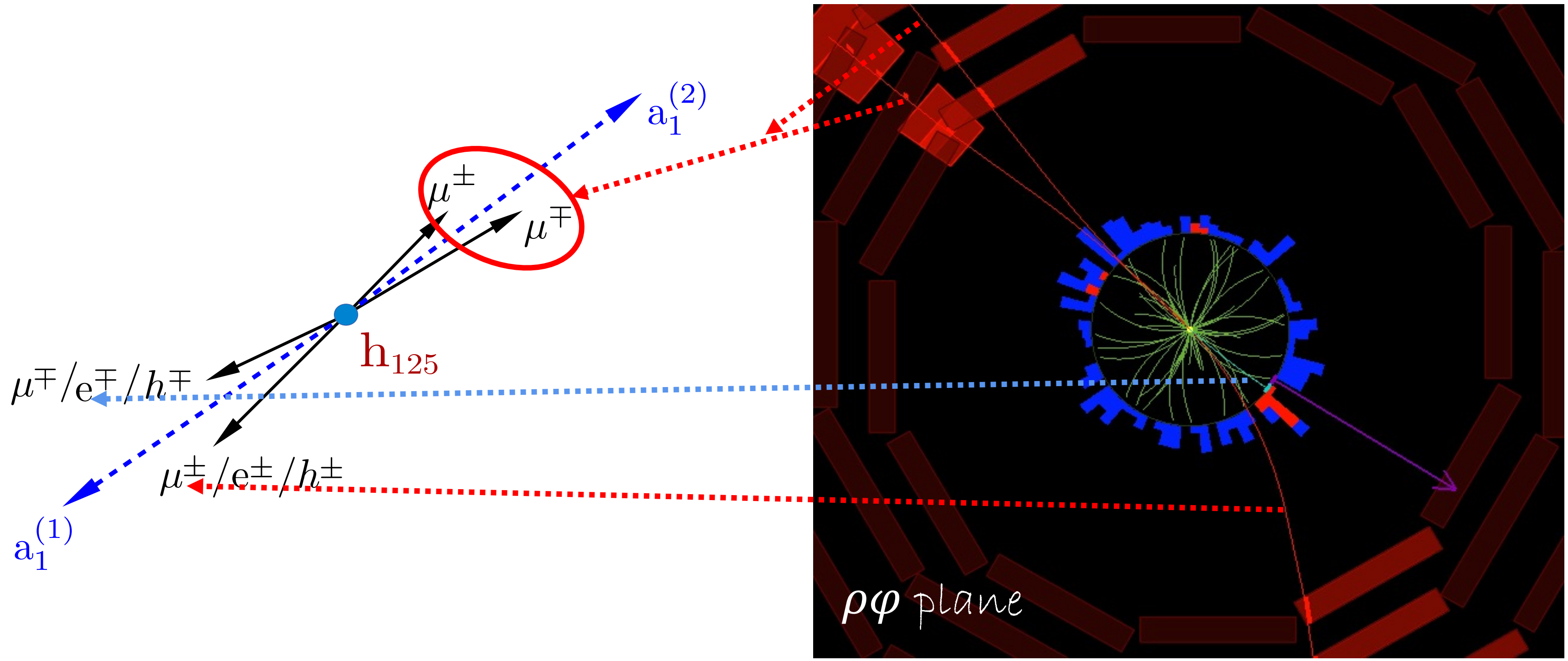
H(125) $\rightarrow a_1 a_1 \rightarrow (\mu\mu)(\tau_{\text{1-prong}}\tau_{\text{1-prong}})$

- target major production mode (ggH)

- tau leptons from $a_1 \rightarrow \tau\tau$ hadronic decays difficult to resolve by dedicated algorithm (Hadron+Strips)

Solution: exploit $a_1 \rightarrow \tau_{\text{1-prong}}\tau_{\text{1-prong}}$ decays in $a_1 \rightarrow \tau\tau$ leg

- experimentally challenging non-isolated leptons in final state



Selection

Online selection: Trigger

> isolated single muon trigger (nearby muons not considered in isolation requirement)

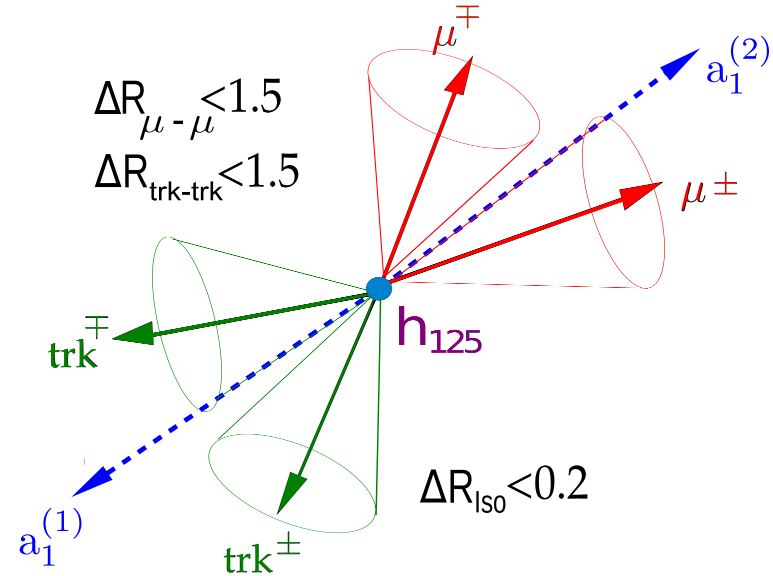
> p_T threshold of 24 GeV (2016, 2018) and 27 GeV (2017)

Offline selection: Trigger

> use of muons and tracks as physics objects

Dimuon pair:
- opposite sign pair of muons
- one muon matches the trigger object
- $p_T(\mu_1)$ > 25 (28 GeV), $p_T(\mu_2) > 3$ GeV
- $|\vec{p}_T(\mu_1) + \vec{p}_T(\mu_2)| > 45$ GeV
- muon-muon pair with highest sum of p_T identified as the $a_1 \rightarrow \mu\mu$ candidate

Ditrack pair:
- opposite sign high purity tracks
- p_T > 2.5 GeV
- $|\vec{p}_T(\mathrm{trk}_1) + \vec{p}_T(\mathrm{trk}_2)| > 10$ GeV
- track-track pair with highest sum of p_T identified as the $a_1 \rightarrow \tau\tau$ candidate



3 categories:
- lepton-lepton
- lepton-hadron
- hadron-hadron

Final selected sample:

> Dimuon+ditrack system (each of the muons and the tracks isolated within ΔR cone of 0.2)

Final discriminant

Binned distribution obtained with a Boosted Decision Tree classifier

> classifier trained to distinguish signal vs. background

> signal class
generated with multidimensional pdf:

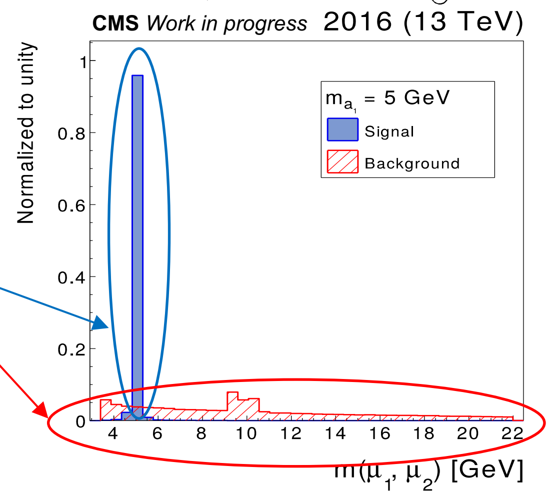
$$f_{tot} = f_{m_{\mu\mu}} \cdot f_{\Delta R(\mu,\mu)} \cdot f_{\Delta R(trk,trk)} \cdot f_{m_{\mu,\mu,trk,trk,MET}}$$

(more details on next slide)

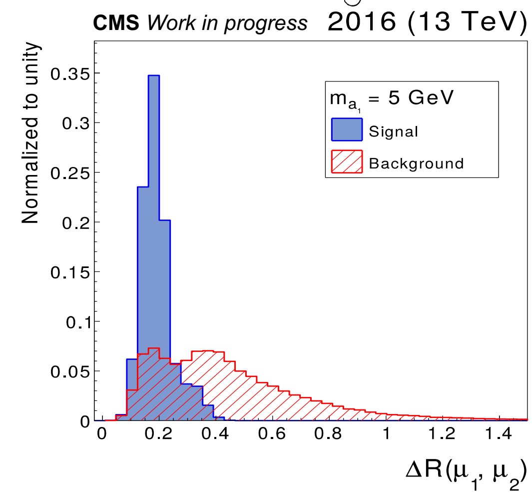
> background class
obtained from data-driven estimation

> individualized training and classification
one classifier per mass hypothesis, per category, per year to maximize discriminating power

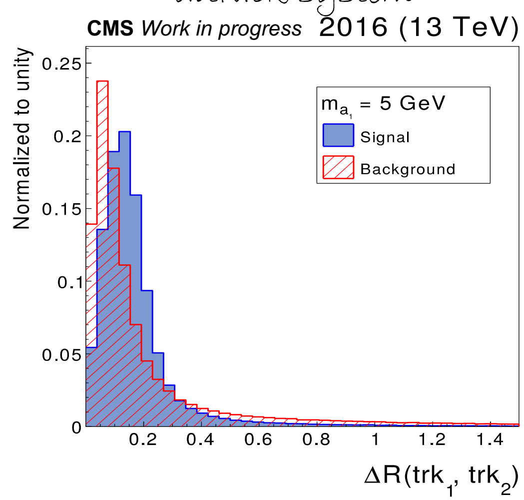
mass of the dimuon system



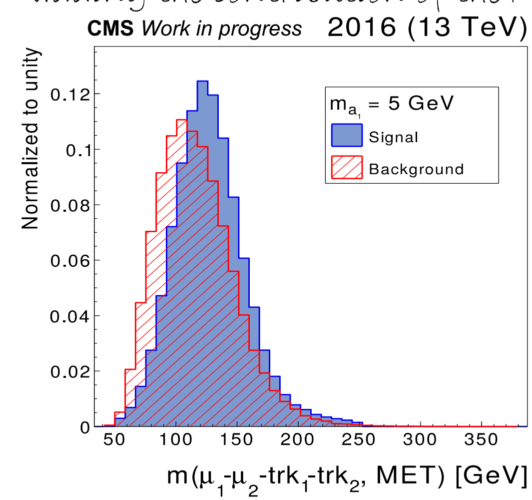
ΔR between both muons of dimuon system



ΔR between both tracks of ditrack system

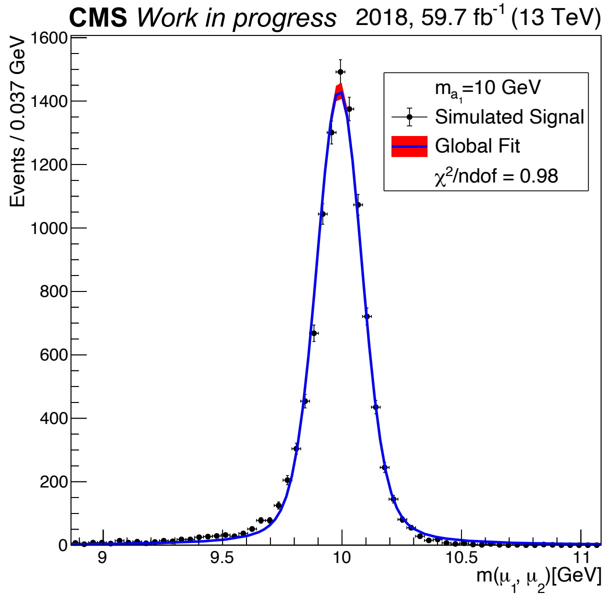


invariant mass of the four objects, adding the contribution of the MET



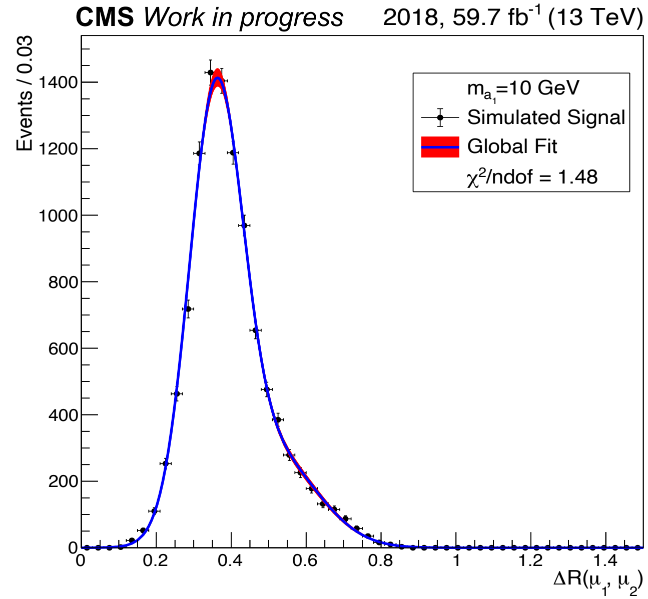
Signal model:

Signal pdf:



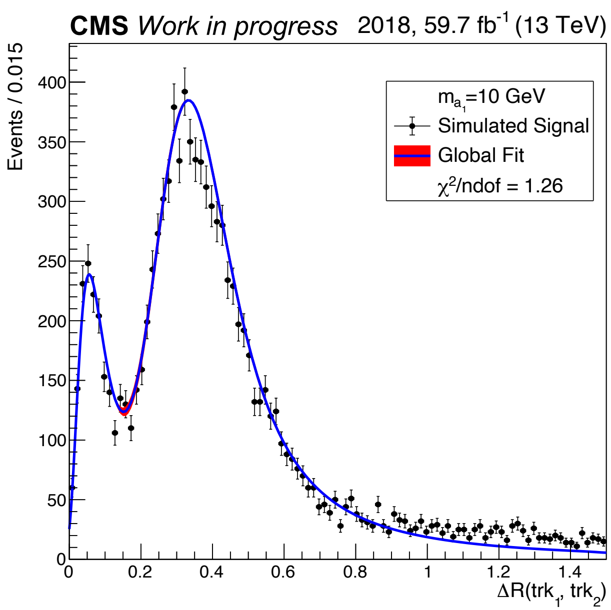
$f_{m_{\mu\mu}}$

convolution of a Breit-Wigner and a Gaussian



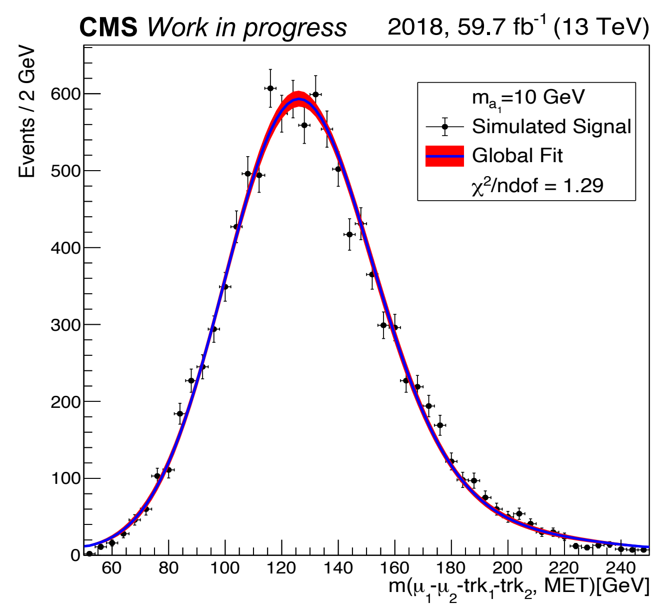
$f_{\Delta R(\mu,\mu)}$

addition of 2 Gaussians



$f_{\Delta R(trk,trk)}$

addition of the convolution of a Landau and a Gaussian with a Landau



$f_{m_{\mu,\mu,trk,trk,MET}}$

convolution of a Landau and a Gaussian

Background model

> estimated using a data-driven procedure

Background composition:

> low mass Drell-Yan, $t\bar{t}$, and QCD events

> QCD contribution includes quarkonium states: ψ', Υ(1S), Υ(2S), and Υ(3S)

Control region	μ-μ	trk-trk
NNNN	$N_{soft} >= 1$	$N_{soft} >= 1$
Soft-Iso	$N_{soft} = 1, 2$	$N_{soft} = 1, 2$
00-Soft-Iso	$N_{soft} = 0$	$N_{soft} = 1, 2$
Same-Sign	$N_{soft} = 0$	$N_{soft} = 0$

N_{soft}: number of "soft" tracks ($p_T > 1$ GeV, $d_{xy} < 1$ cm, and $d_z < 1$ cm) within ΔR cone of 0.2

> shape of multivariate distribution derived in control region **NNNN**

> validation with additional control regions (**Soft-Iso** and **00-Soft-Iso**) relaxing isolation requirement (closure test in next slide)

Background validation

Closure test:

Shape in control region NNNN compared to sideband regions closer to the signal region for the hadron-hadron category

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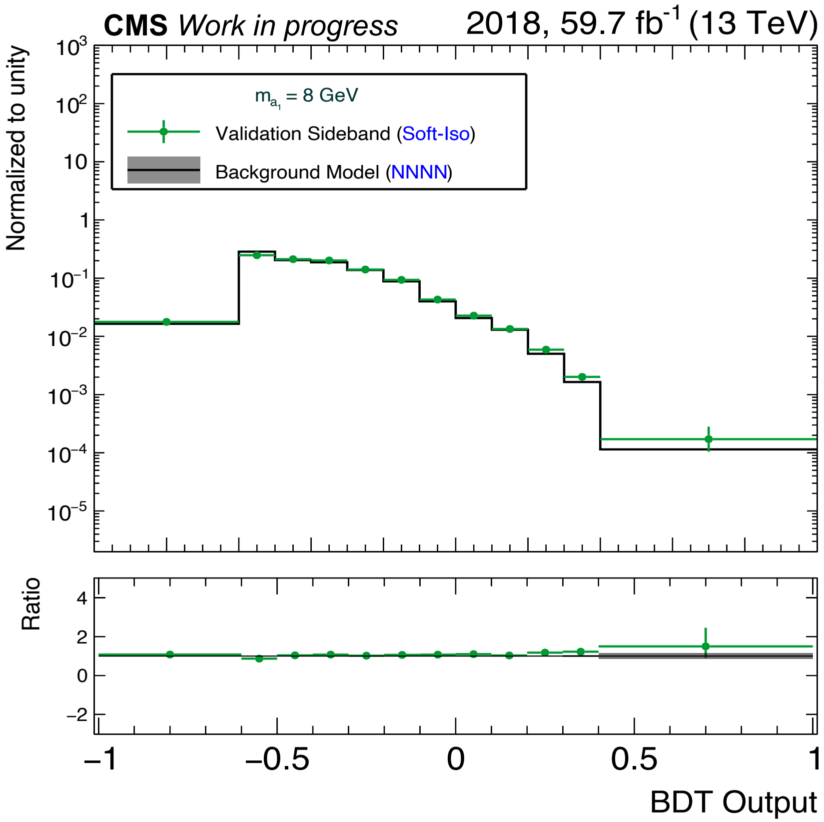
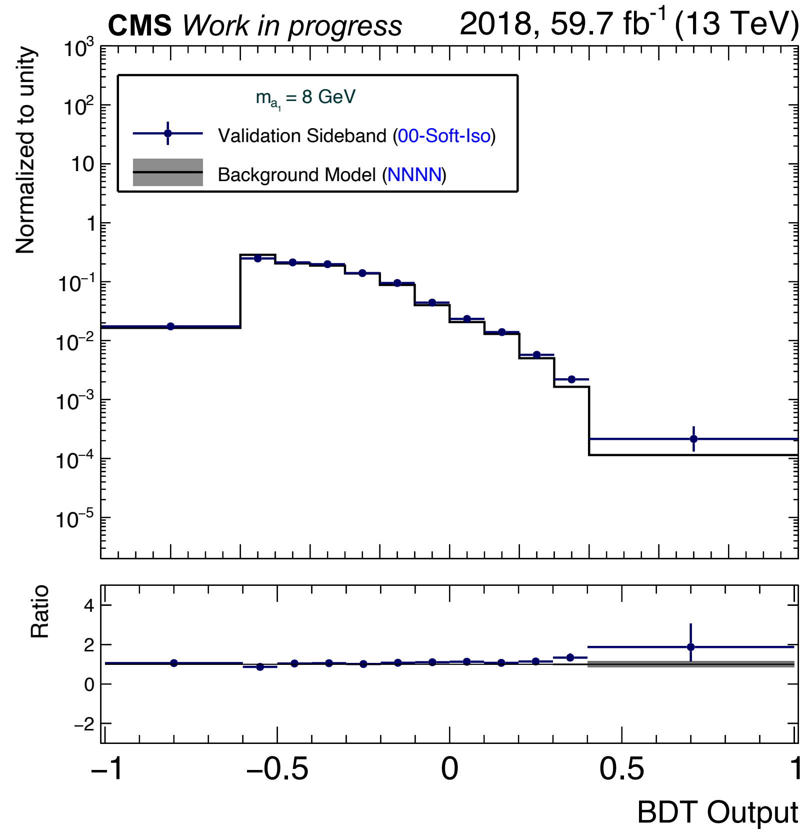
Soft-Iso



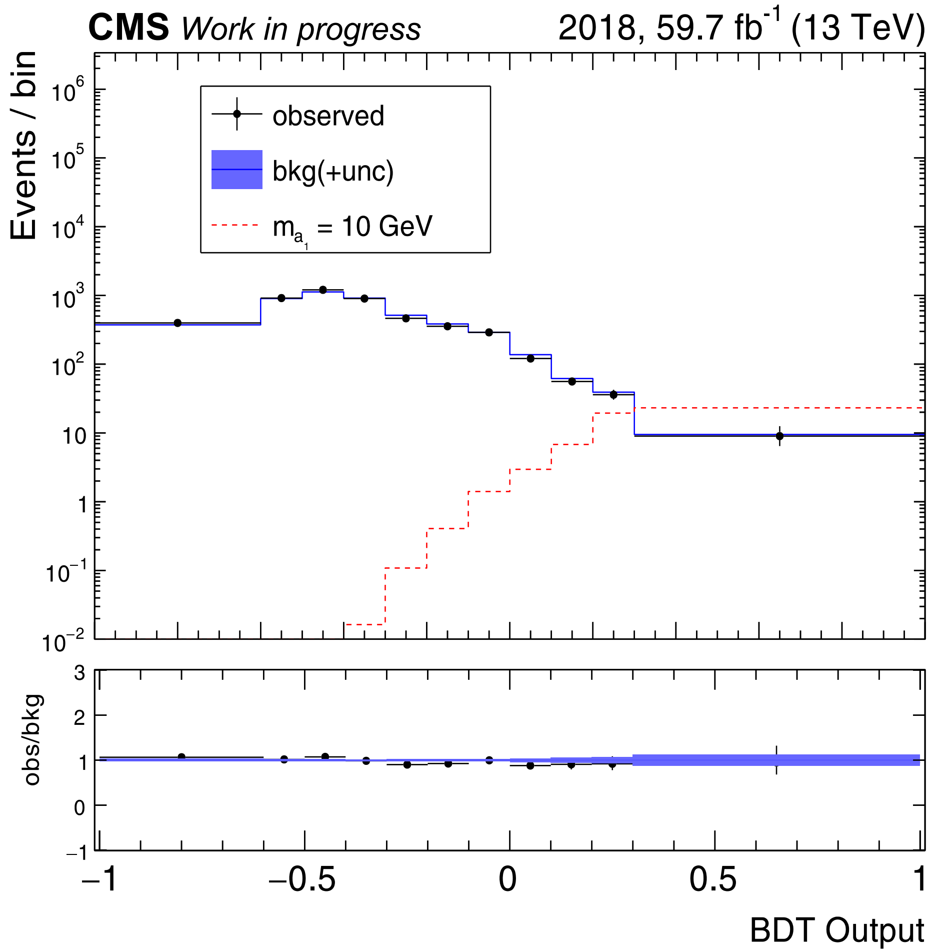
00-Soft-Iso



> good agreement observed within the uncertainties

Final discriminant: BDT output distribution

> Background distribution obtained after performing fit to data under background-only hypothesis in lepton-hadron category



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Other two categories in backup

> Benchmarking signal normalization events (assuming SM xsec in ggH)

> **Branching ratio:** BR(H(125) $\rightarrow a_1 a_1 \rightarrow \mu\mu\tau\tau) = 0.01$

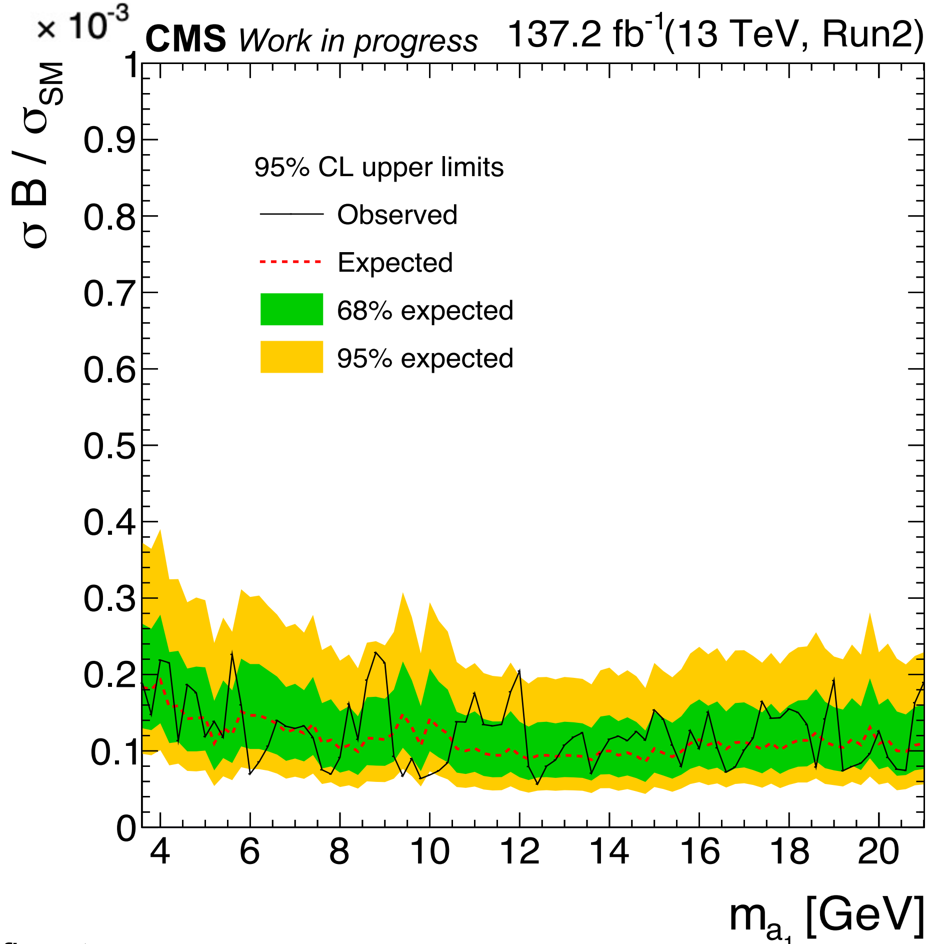
Systematic uncertainties

Source	Value	Affected sample	Type
Stat. unc. related to size of CR NNNN		bkg.	bin-by-bin
Extrapolation unc. in CR Same-Sign		bkg.	shape
Integrated luminosity	2016, 2017, 2018 2.5%, 2.3%, 2.3%	signal	norm.
Muon id. and trigger efficiency	2% per muon	signal	norm.
Track Iso.	6–9% per track	signal	norm
MC stat. unc. propagated in parameters of the pdf signal model (1 nuisance per parameter)		signal	shape
Theoretical uncertainties in the signal acceptance			
μ_R and μ_F variations	0.8–2%	signal	norm.
PDF	1–2%	signal	norm.
Theoretical uncertainties in the signal cross sections			
$\mu_{R,F}$ variations ($gg \to H(125)$)	5–7%	signal	norm.
PDF ($gg \to H(125)$)	3.1%	signal	norm.

> uncertainties in muon (track) momentum scale of 0.2 (0.4) % ---> negligible effect on final results

Results

> evaluated in terms of 95% CL upper limits on: BR(H(125) $\rightarrow a_1 a_1 \rightarrow \mu\mu\tau\tau$)



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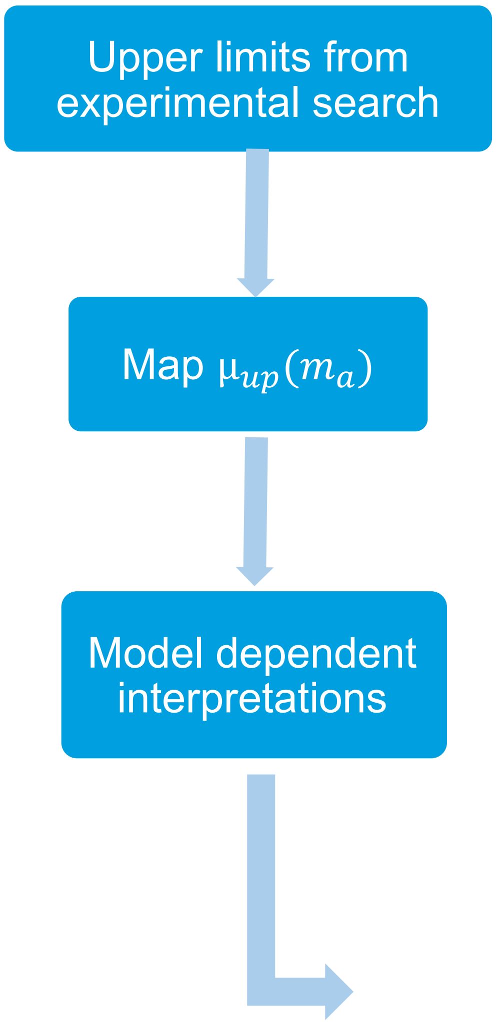


> no significant excess

> sensitivity to BR per mil level

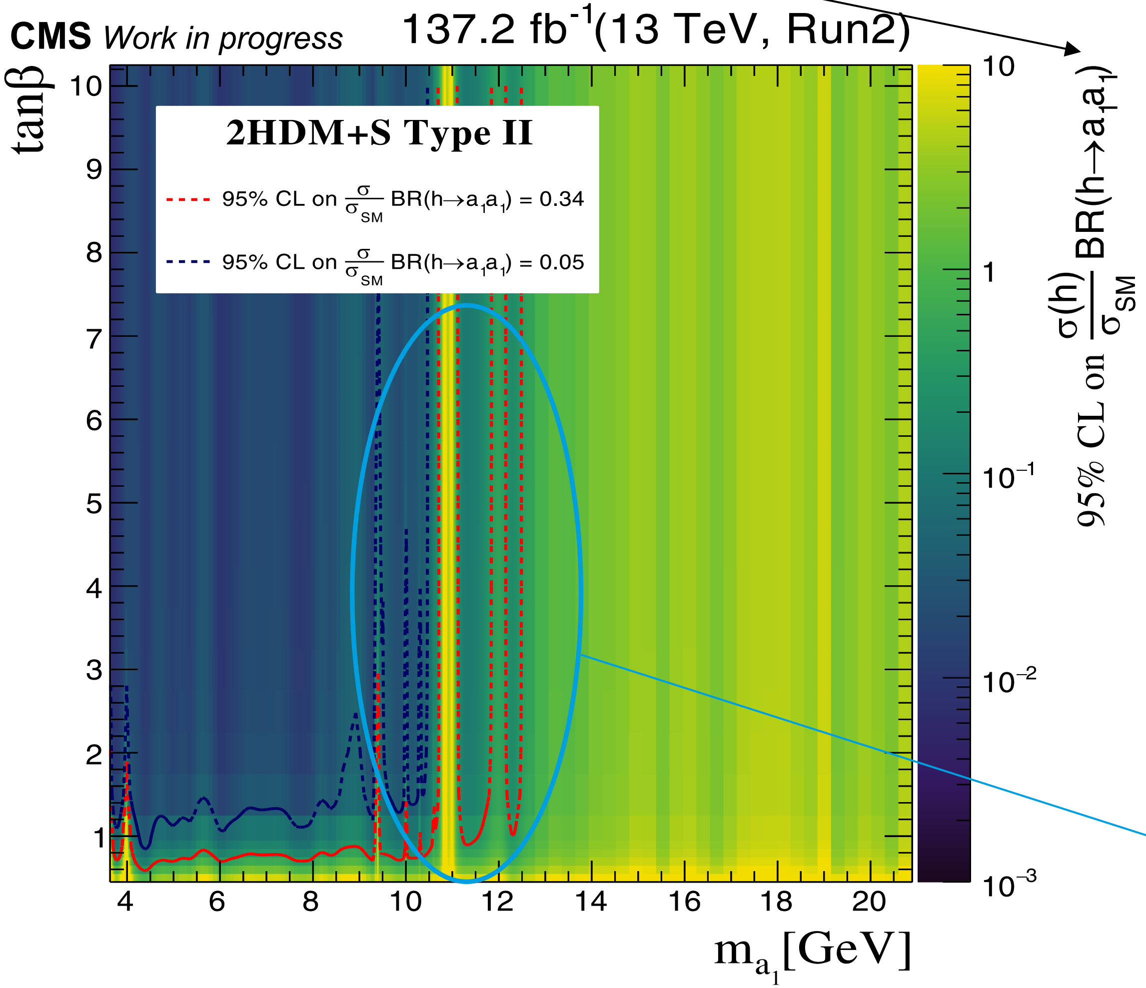
> up to 4.2 times more sensitive than 2016-only CMS published result

Interpretation of the results in the 2HDM+1S context

$$((\sigma_h/\sigma_{SM}) \cdot \mathcal{B}(h \to aa))_{\text{up}} = \frac{\boxed{\mu_{\text{up}}(m_a)}}{2\,\boxed{\mathcal{B}(a \to x\bar{x}; m_a, \tan\beta) \cdot \mathcal{B}(a \to y\bar{y}; m_a, \tan\beta)}}$$

from experimental search

theoretical predictions of the model



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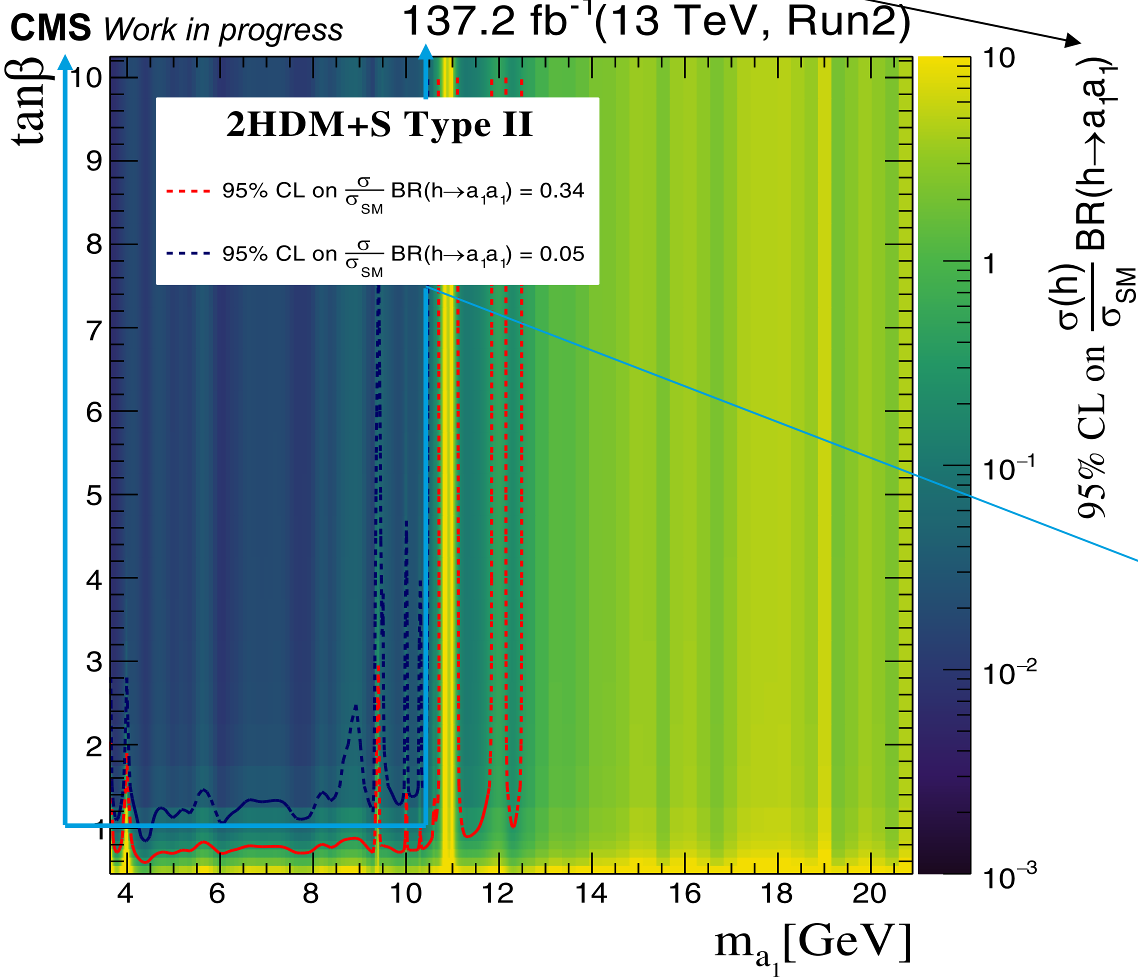
peak-like shape of contours due to a_1-quarkonium mixing

Interpretation of the results in the 2HDM+1S context

$$((\sigma_h/\sigma_{\rm SM})\cdot\mathcal{B}(h\to aa))_{\rm up} = \frac{\boxed{\mu_{\rm up}(m_a)}}{2\,\boxed{\mathcal{B}(a\to x\bar{x};m_a,\tan\beta)\cdot\mathcal{B}(a\to y\bar{y};m_a,\tan\beta)}}$$

from experimental search

theoretical predictions of the model



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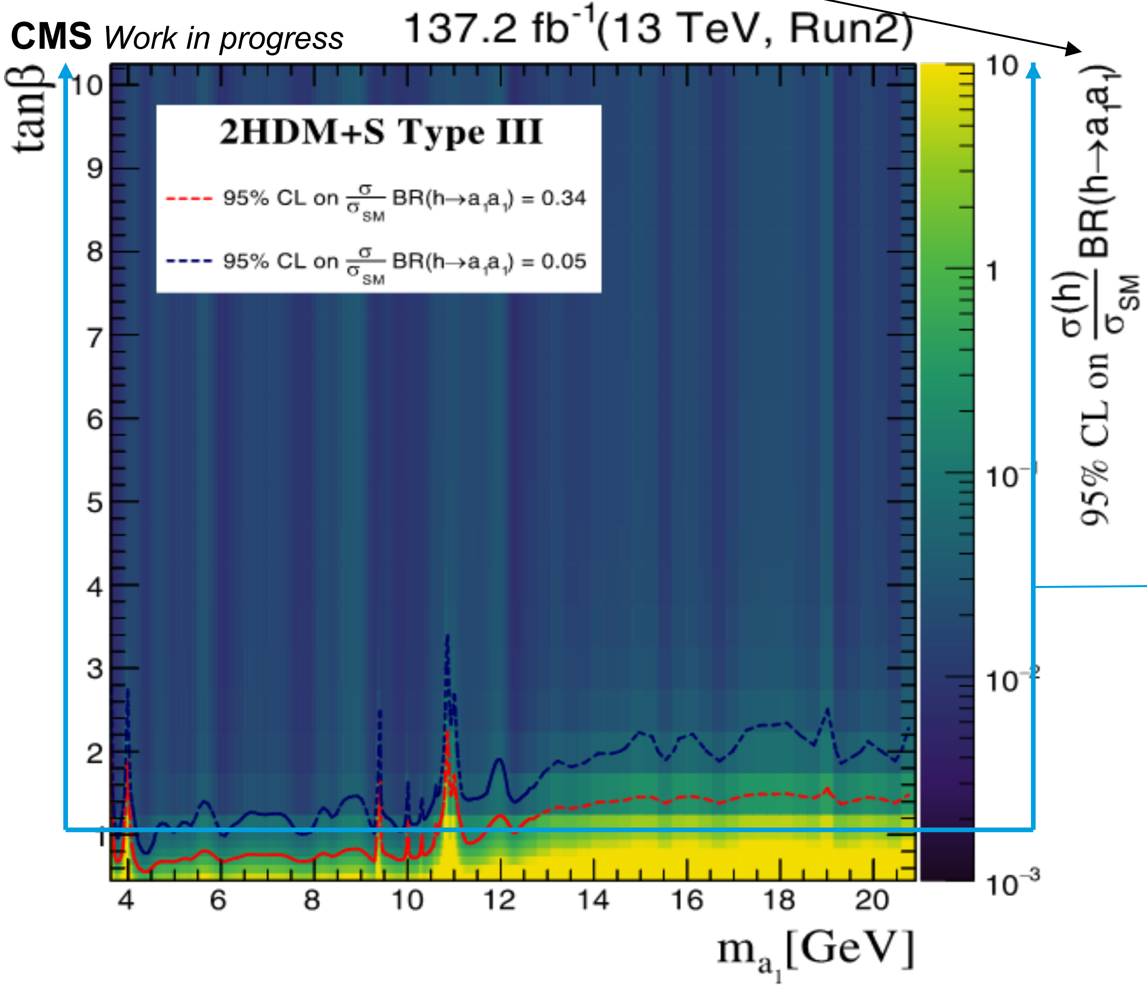
sensitive for values of tanβ > 1 and m_{a_1} below the b-quark pair threshold

Interpretation of the results in the 2HDM+1S context

$$((\sigma_h/\sigma_{\mathrm{SM}}) \cdot \mathcal{B}(h \to aa))_{\mathrm{up}} = \frac{\boxed{\mu_{\mathrm{up}}(m_a)}}{2\,\boxed{\mathcal{B}(a \to x\bar{x}; m_a, \tan\beta) \cdot \mathcal{B}(a \to y\bar{y}; m_a, \tan\beta)}}$$

from experimental search

theoretical predictions of the model



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highly sensitive for tanβ >1

Summary

Analysis searching for the $\mathrm{H(125)} \rightarrow \mathrm{a_1 a_1}$ decay in final states with 2 muons and 2 tau leptons with Run 2 data is presented

> Search covers range of $\mathrm{m_{a_1}}$ between 3.6 and 21 GeV

> machine learning approach targeting the (semi-)boosted topologies

> **Signal extraction:** maximum likelihood fit applied to BDT output distribution

> Sensitivity evaluated in terms of observed 95% CL limit on $\sigma \cdot \mathrm{BR(H(125)} \rightarrow \mathrm{a_1 a_1} \rightarrow \mu\mu\tau\tau)/\sigma_{\mathrm{SM}}$ ranging between 0.57 x 10^{-4} ($\mathrm{m_{a_1}}$ = 12.4 GeV) and 2.29 x 10^{-4} ($\mathrm{m_{a_1}}$ = 8.8 GeV)

> no evidence of exotic decays of h_{125} to light bosons

> exclusion power of analysis covers wide range of the parameter phase space of the different types of 2HDM+1S

> most stringent limits obtained for scenarios with enhanced couplings to leptons

more direct searches and precision measurements of the properties of $\boldsymbol{h_{125}}$ to come with the Run 3 data

Stay tuned!

Thank you!

Contact

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Backup

> **Additional material**

Final discriminant: BDT output distribution

> Background distribution obtained after performing fit to data under background-only hypothesis

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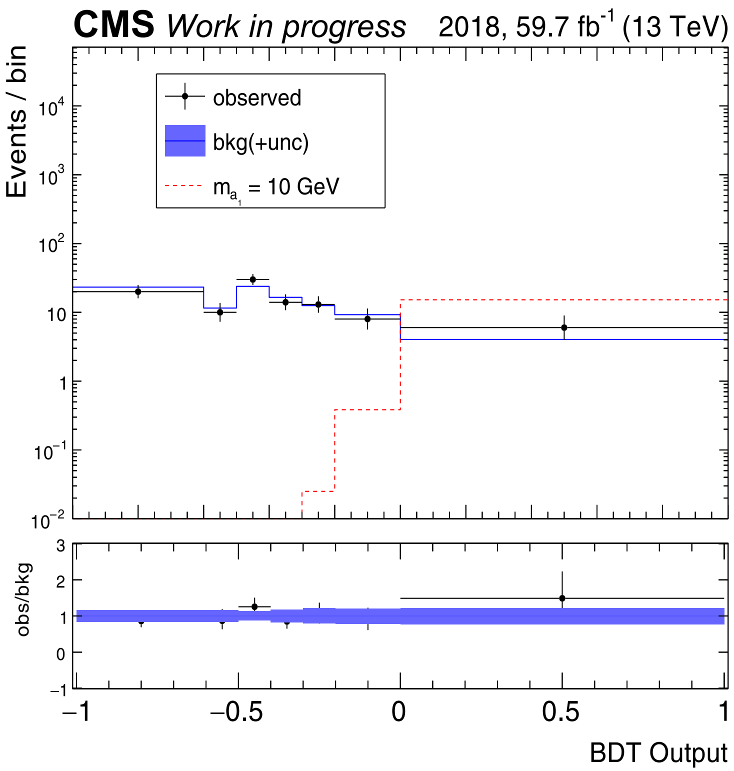
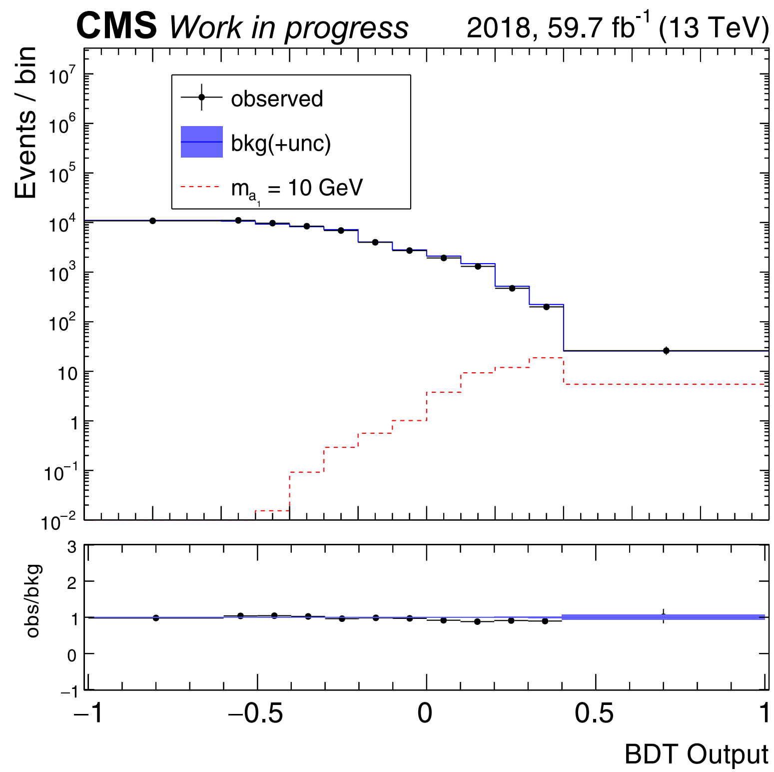
lepton-lepton



hadron-hadron



> Benchmarking signal normalization events (assuming SM xsec in ggH)

> **Branching ratio:** BR(H(125) $\rightarrow a_1 a_1 \rightarrow \tau\tau\tau\tau) = 0.01$

Results

> evaluated in terms of 95% CL upper limits on: BR(H(125) → $a_1 a_1$→μμττ)

> Combination of all channels for 2016, 2017, and 2018 datasets

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