Searches for exotic decays of a 125 GeV Higgs boson at ATLAS & CMS

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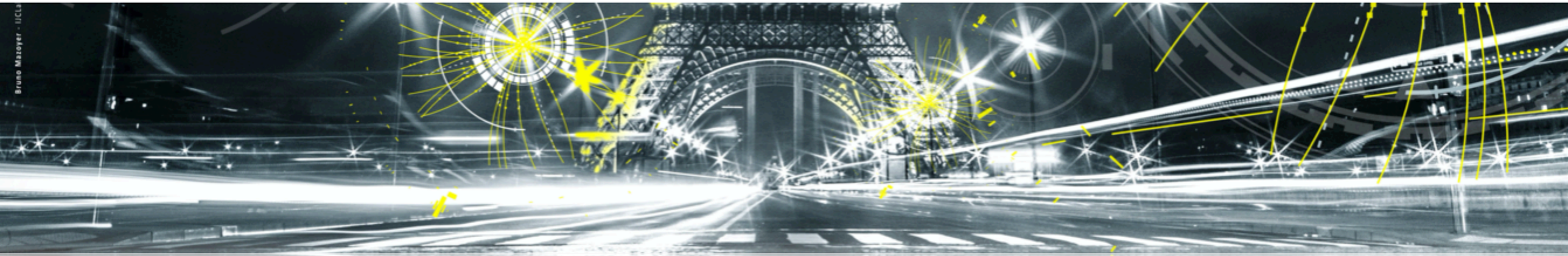


The 8th Annual Large Hadron Collider Physics, 25-30 May 2020

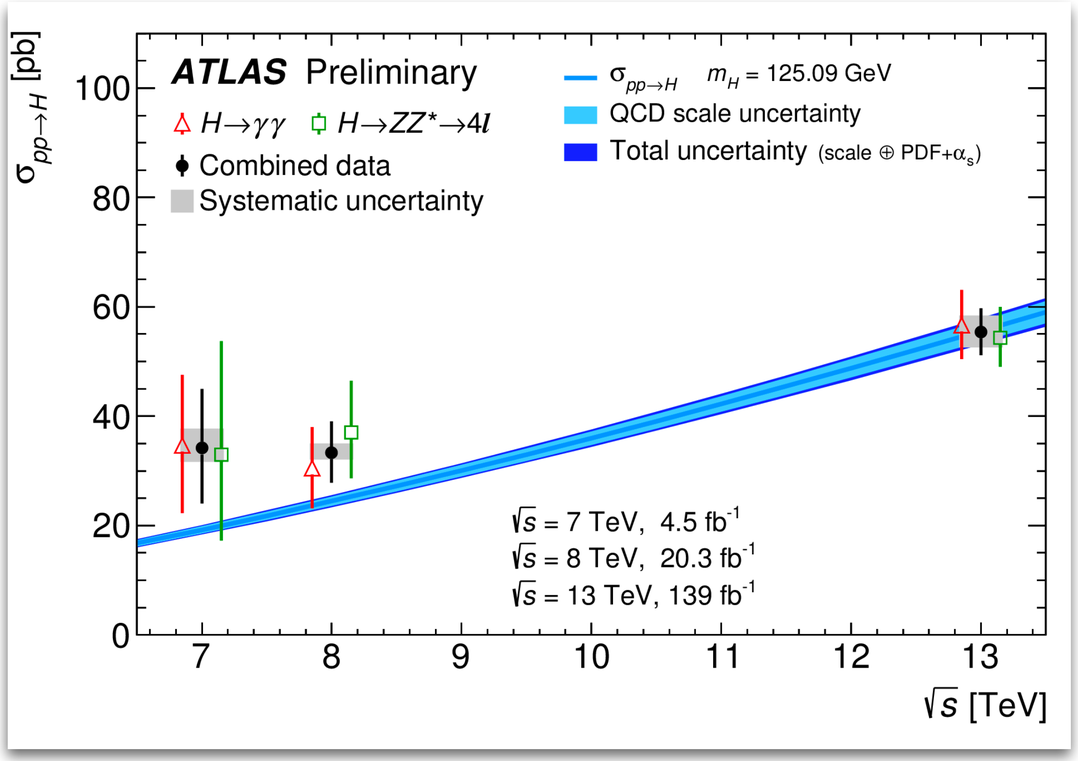
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

CMS Compact Muon Solenoid

ATLAS EXPERIMENT

Introduction

- The discovered 125 GeV Higgs boson is compatible with the Standard Model (SM) prediction.
- However, the SM **cannot** provide complete descriptions of the following issues:
  - "hierarchy problem" ($m_h << m_{Planck}$)
  - existence of dark matter and dark energy
  - existence of neutrino masses
  - matter-antimatter asymmetry
- Strong indications that the SM is only a **low-energy approximate** of a more advanced theory.
- Many theories beyond the Standard Model (BSM) were developed to overcome the limitations of the SM (e.g. SUSY, extra Higgs doublets, composite Higgs, Higgs portals to dark matter…) .
- Looking at **new/exotic Higgs boson decays** provides us a unique approach to BSM searches.



Exotic Higgs searches at ATLAS & CMS

- Search for Higgs boson decaying to
  - non-SM particles: **light scalars (→SM particles)** or new stable particles
  - SM particles: rare or **forbidden** in SM

Higgs decays to new light scalars		Lepton flavour violating	
$h \to aa \to 4b/2b2\mu$	ATLAS, CMS	$h \to e\tau$	ATLAS, CMS
$h \to aa \to 4\tau/2b2\tau/2\mu2\tau$	CMS	$h \to \mu\tau$	ATLAS, CMS
$h \to aa \to 4\mu$	ATLAS, CMS	$h \to e\mu$	ATLAS
$h \to aa \to \gamma\gamma gg$	ATLAS		
$h \to Za/Z\eta_c/ZJ/\psi \to \ell\ell j$	ATLAS		
$h \to Z\rho^0/Z\varphi$	CMS		

http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG/index.html

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ResultswithData2018

Two-Higgs-doublet model + one complex scalar singlet (2HDM+S)

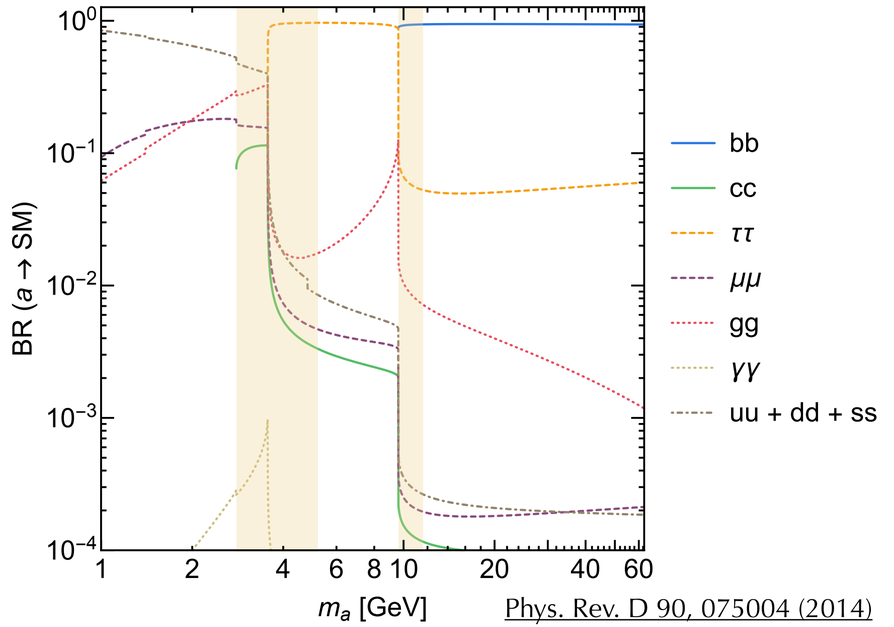
- The **2HDM** is one of the simplest extensions of the SM (motivated by MSSM, axion models…)
- Two Higgs doublets ϕ_1, ϕ_2 , after symmetry breaking =>
  - (h, H) neutral Higgs bosons which are CP-even (scalar),
  - (A) neutral Higgs boson and CP-odd (pseudo-scalar),
  - ($H^{\pm}$) charged Higgs bosons
  - tanβ: the ratio of the VEV of the two Higgs doublets
  - α: the mixing angle between the CP-even Higgs bosons
- Different categories depending on the type of interaction of the two doublets with quarks and charged lepton.
- In addition, the extra **complex scalar singlet** only couples to the two Higgs complex fields in the **potential** and has **no Yukawa couplings =>** light pseudo-scalar (a)
  - all of its couplings to SM fermions are through mixing of the scalar with the Higgs fields, and **small** to preserve the SM nature of the Higgs sector

Models which lead to natural flavour conservation. The superscript i is a generation index. By convention, the u_R^i always couple to Φ_2.

Model	u_R^i	d_R^i	e_R^i
Type I → Fermiophobic	Φ_2	Φ_2	Φ_2
Type II → MSSM-like	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

G.C. Branco et al. / Physics Reports 516 (2012) 1–102

Type II, tan β = 5

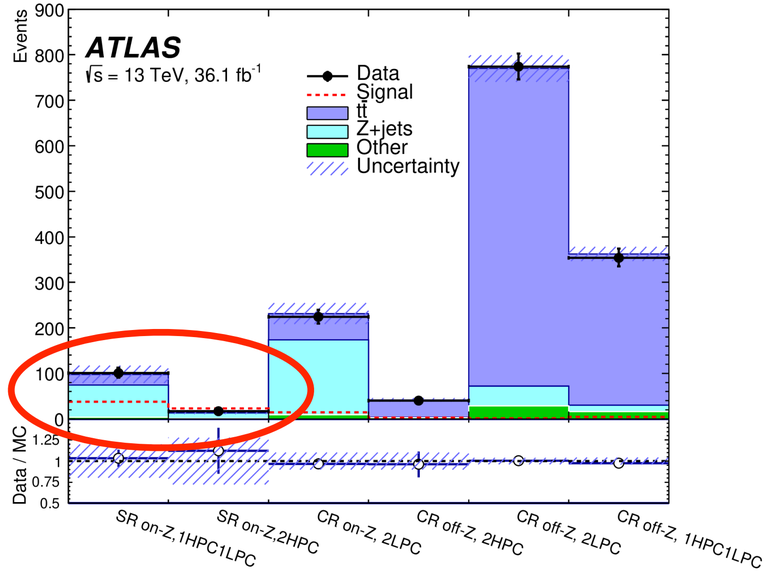


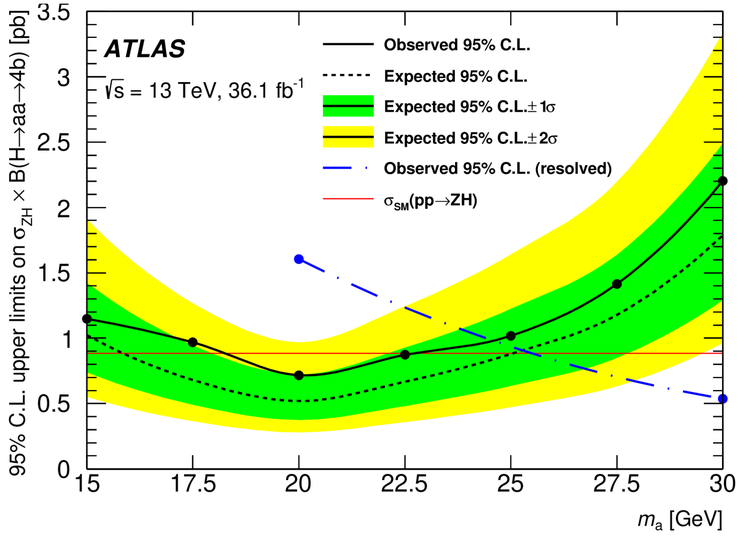
Phys. Rev. D 90, 075004 (2014)

Search for h→aa→4b

CERN-EP-2020-061

- In most of 2HDM+S models, B(a → bb) dominates in the range of ma > 10 GeV
- This analysis was recently extended in the ZH production to cover the mass regime **15 GeV ≤ m_a ≤ 30 GeV**
- To investigate the boost case of a → bb, a special BDT based-on track-jets is trained for reconstruction and identification
- No significant excess of events above the SM background prediction is observed
- This novel search improves the expected limit on σxB for m_a = 20 GeV by **a factor of 2.5** w.r.t. the previous result



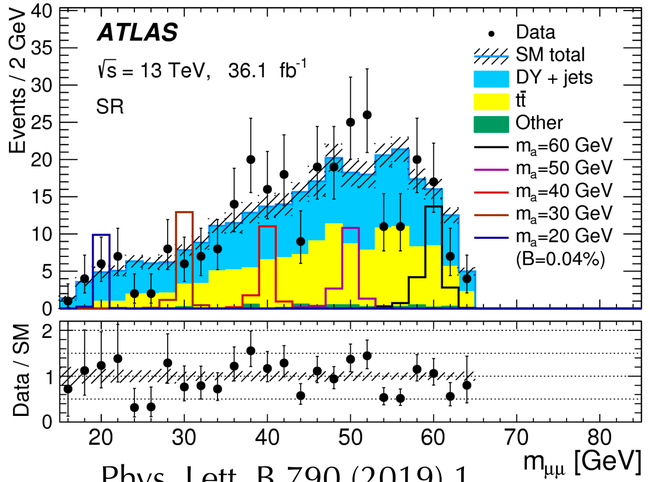


Search for h→aa→2μ2b in ggF and VBF productions

- In the Type-III 2HDM+S (with enhanced lepton couplings), B(a → μμ) can also be relatively large

  - **ATLAS**: Exactly 2 b-tagged jets, kinematic fit to $m_{bb\mu\mu}$, the floating normalization of the ttbar and DY backgrounds are determined from CRs
  - Observed $(\sigma_H/\sigma_{SM})\times$ B upper limit @95%CL: **(1.2–8.4)×10⁻⁴** in the a-boson mass range of 20 to 60 GeV

  - **CMS**: 3 categories based on b-tagged jets, analytic functions are used to model both signal and backgrounds, simultaneously unbinned likelihood fitting
  - Observed $(\sigma_H/\sigma_{SM})\times$ B upper limit @95%CL : **(1–7)×10⁻⁴** for the mass range 20 to 62.5 GeV



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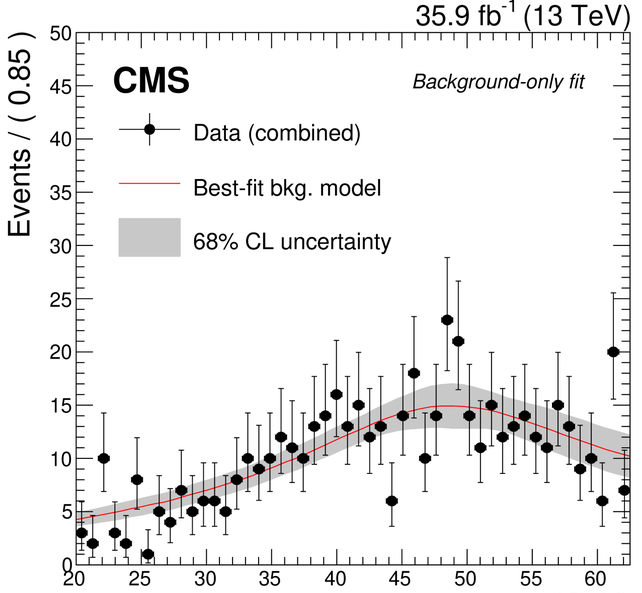
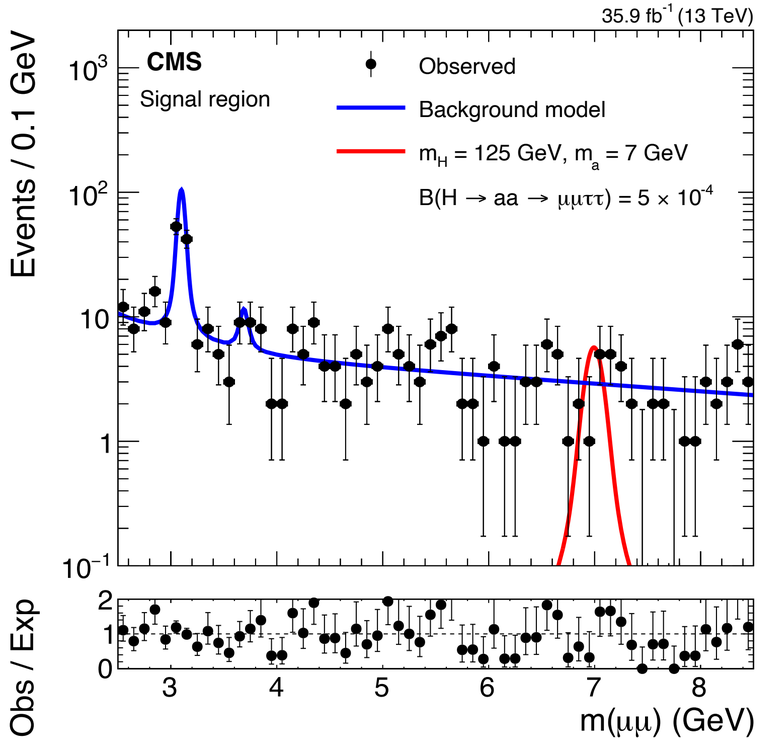


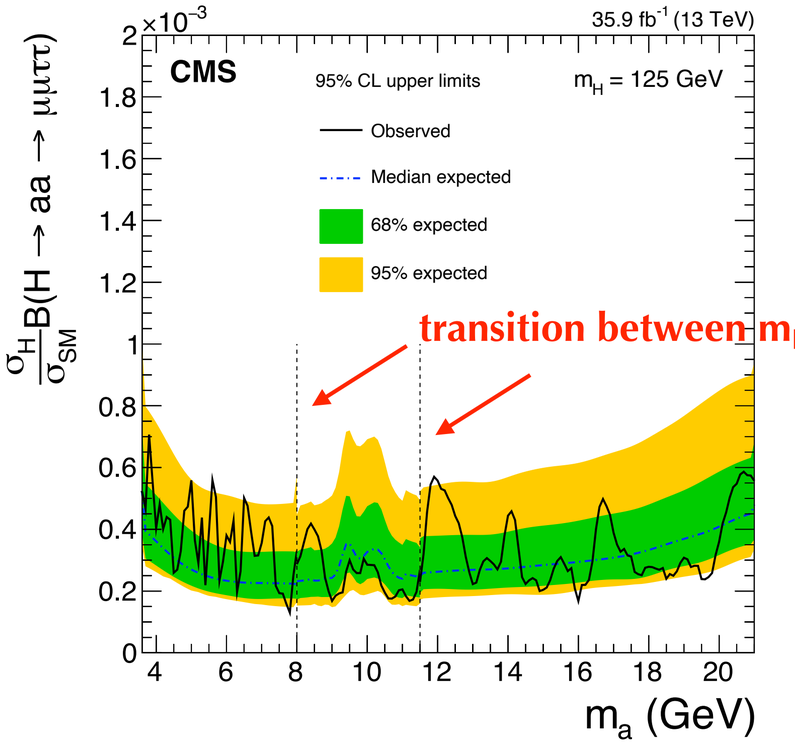
Phys. Lett. B 795 (2019) 398

Search for h→aa→2μ2τ

arXiv:2005.08694

- **3.6 GeV < m_a < 21 GeV**, the μμ and the ττ pairs have high Lorentz boost and are collimated.
- A special technique is developed for boosted τ lepton pair reconstruction (a → $\tau_\mu\tau_h$) base on hadron-plus-strips algorithm
- The 2D fit of m(μμ) vs. m($\tau_\mu\tau_h$) is performed in data, three m(μμ) ranges: [2.5,8.5], [6,14], and [11,25].

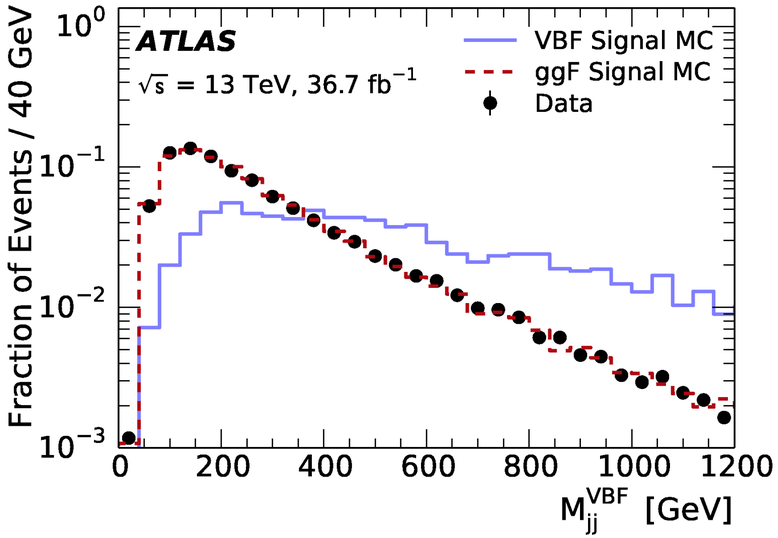


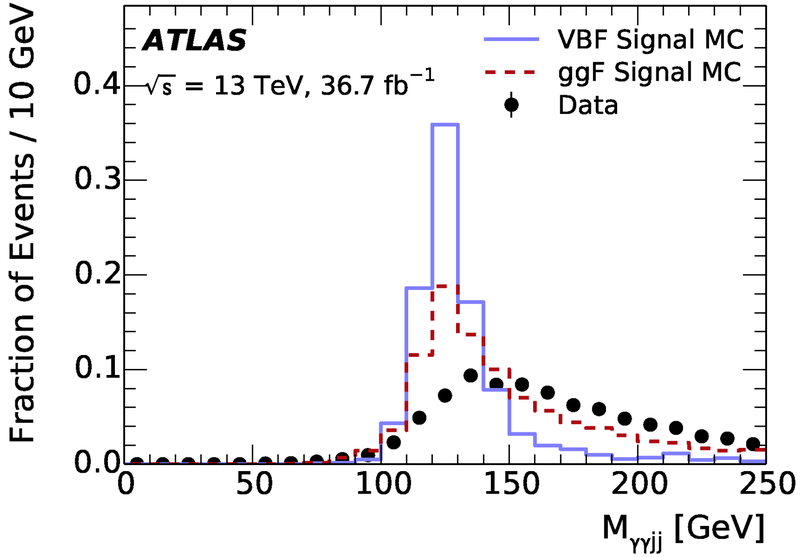


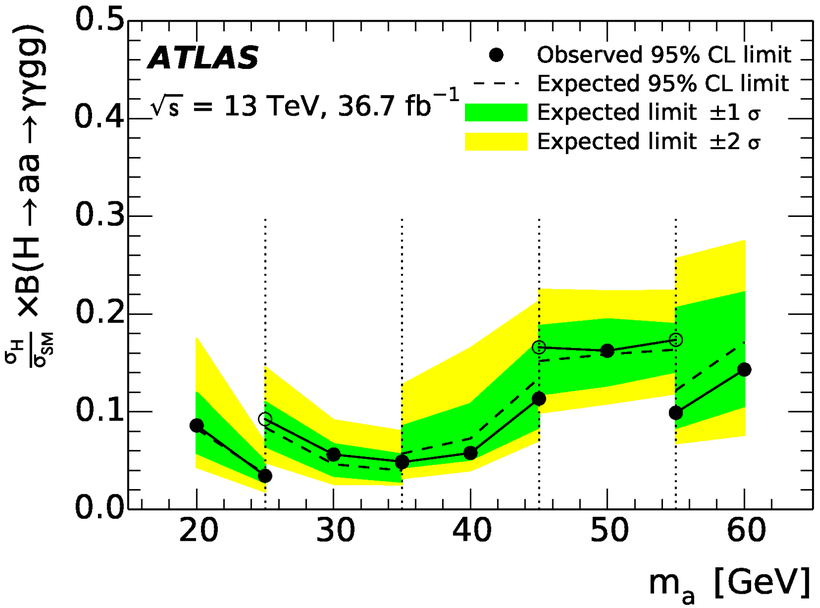
Search for h→aa→γγgg

Phys. Lett. B 782 (2018) 750

- **20 GeV < m_a < 60 GeV**
- Selecting the VBF Higgs production, more effective suppression of the background.
  - ggF production mode has a larger cross-section, but is overwhelmed by the γγ+multi-jet background.
- Events are required to have at least 4 jets
- The observed 95%CL upper limit is set for σxB(H → aa → γγgg) < **3.1-9.0 pb** depending on m_a





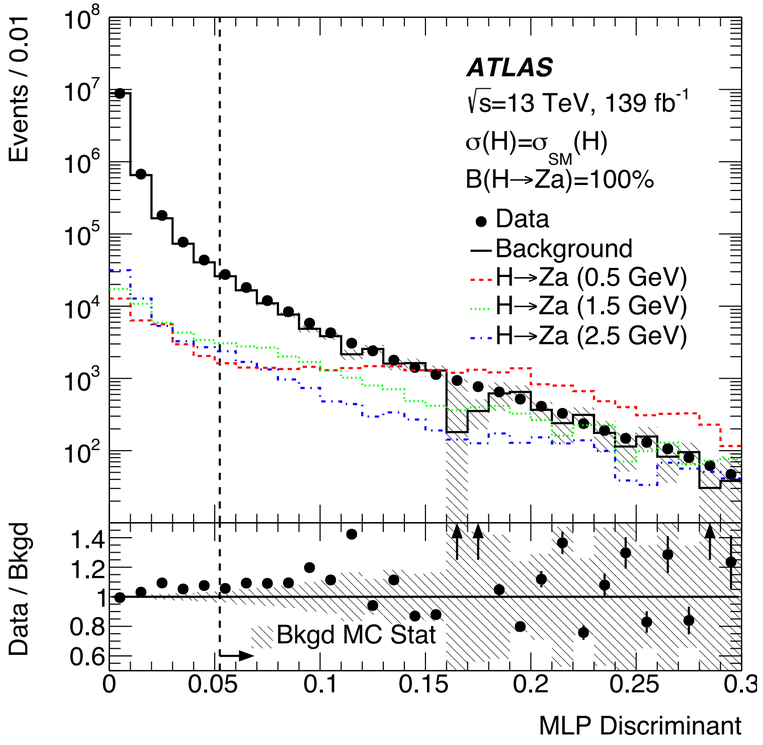


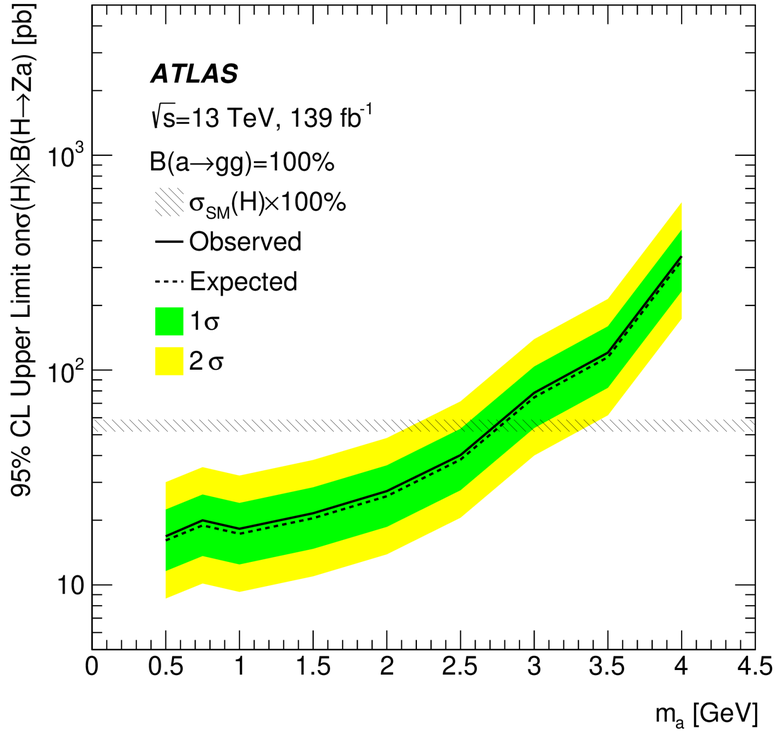
NEW

Search for h → Z(ℓℓ)a,h → Z(ℓℓ)η_c, h → Z(ℓℓ)J/ψ

arXiv:2004.01678

- Search for Higgs boson decays into a Z boson (leptonic decays) and a light pseudo-scalar/meson to **a single jet**
- Jet substructure variables are used for the reconstruction of this light, boosted, hadronic pseudo-scalar/meson
  - individual substructure variables are combined using machine learning techniques
  - a multilayer perceptron (MLP) classifier is used for event selection
- Data-driven estimation for the total background





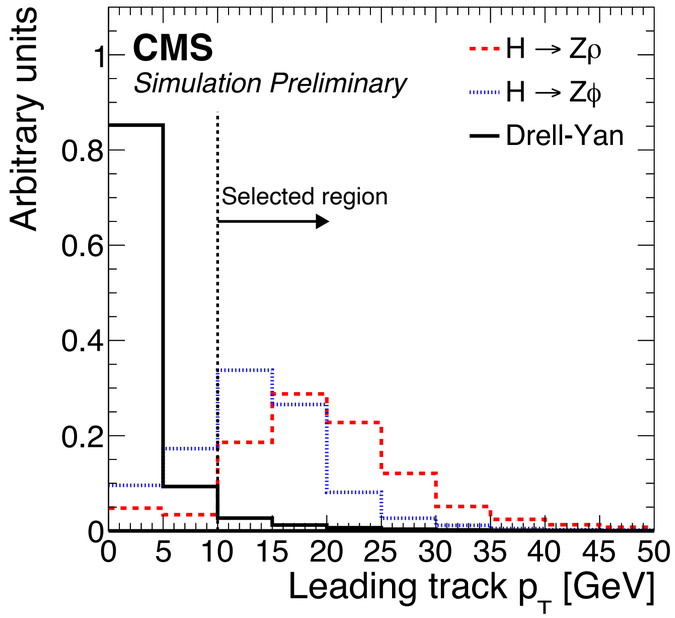
95% CL **observed** upper limits set:
σxB(H → aa): **17–340 pb** for m_a from 0.5 GeV to 4 GeV

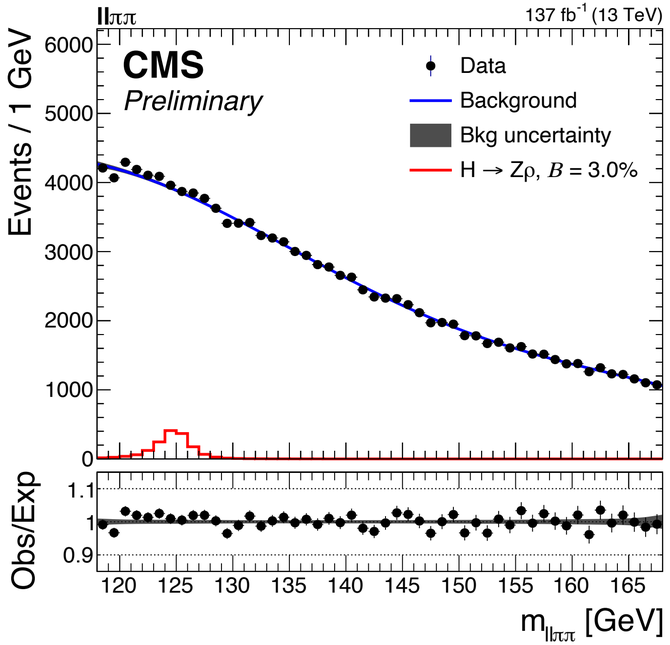
95% CL **observed** upper limits set:
σ(pp → H)B(h → Zη$_c$): 110 pb
σ(pp → H)B(h → Z J/ψ):100 pb

Search for h → Z(ℓℓ)ρ⁰(770) / Z(ℓℓ)φ(1020)

CMS PAS HIG-19-012

- Select events with a Z(ℓℓ), and the ρ⁰ or φ mesons decaying into pairs of pions or kaons.
- The meson candidate is selected as a pair of oppositely charged particle tracks
  - p_T > 1 GeV, ΔR < 0.1, good separation with lepton tracks of the Z boson
  - at least one of the tracks must have p_T > 10 GeV, isolated di-track system
- Main background: Drell–Yan Z → ℓℓ with a genuine or misidentified meson candidate, determined in data sidebands



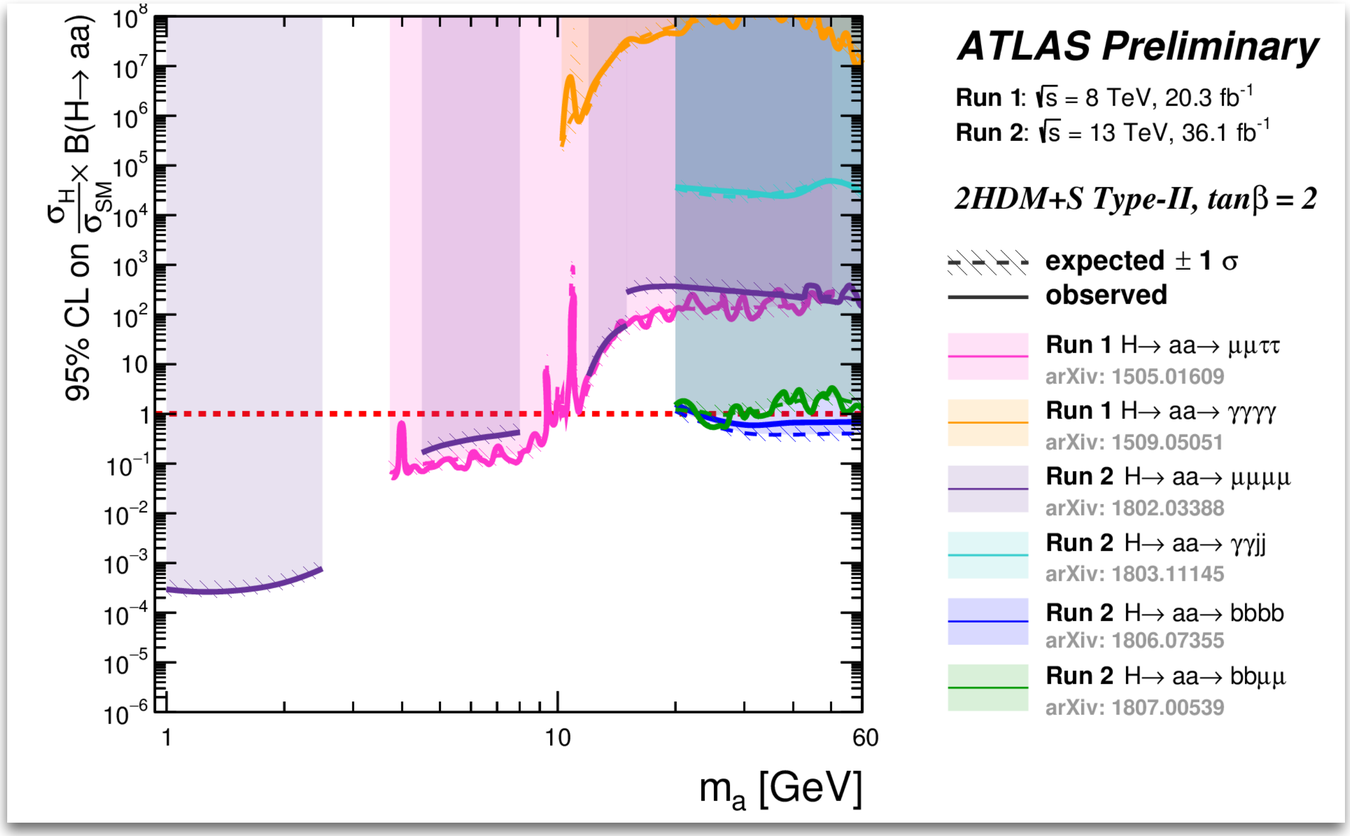


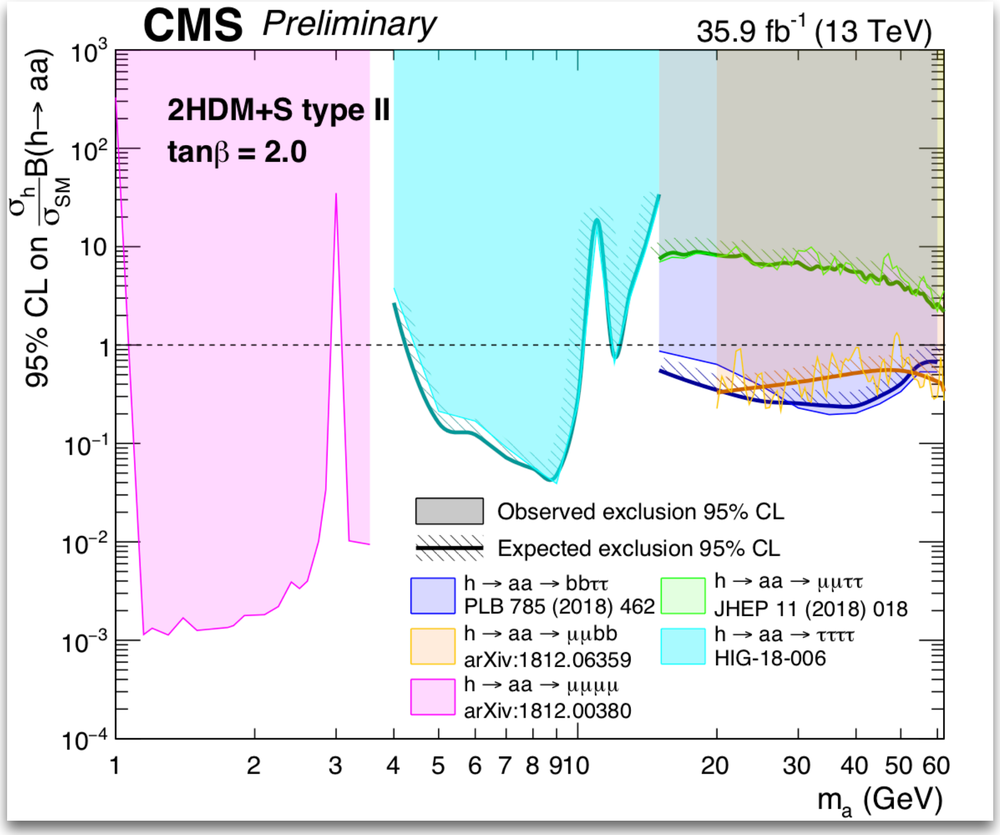
No significant excess above the background model is observed.

95% CL **observed** upper limits set:
B(H → Zφ) < 0.36% – 0.58%
B(H → Zρ⁰) < 1.21% – 1.89%
depending on the polarization scenarios

Summary plot of 2HDM+S

To be updated with full Run 2 data!





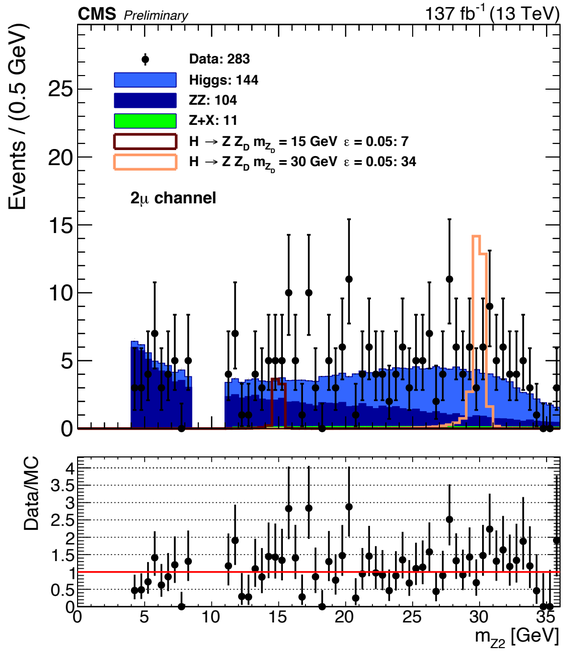
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/HDBS/

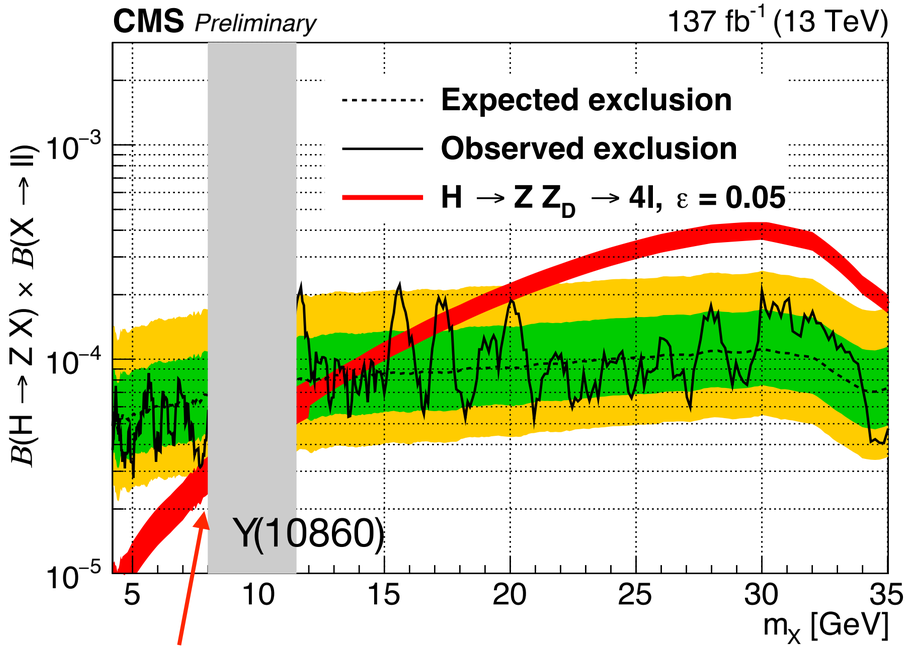
https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryResultsHIG

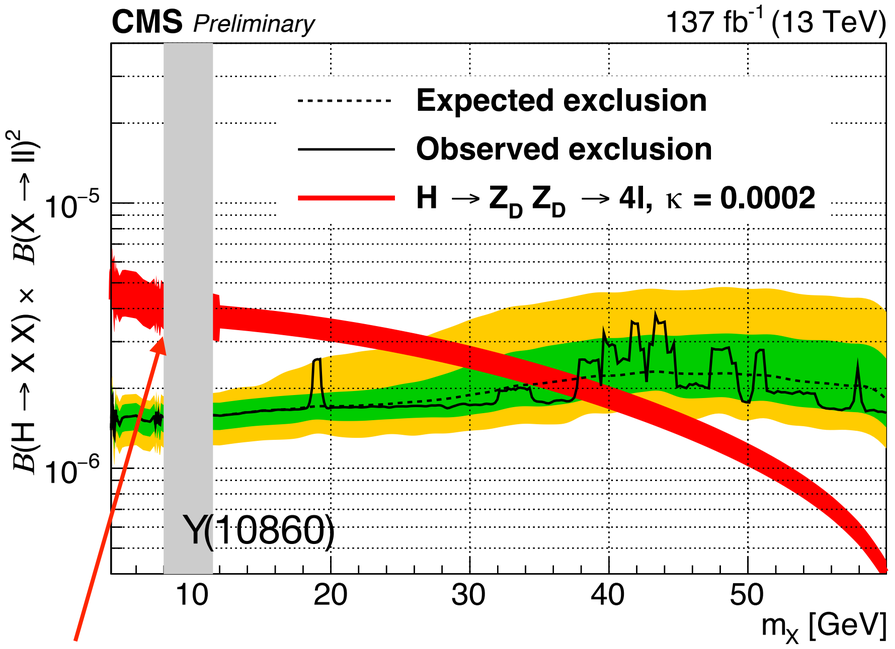
Search for $h \to ZZ_d/Z_dZ_d \to 4\ell$

CMS PAS HIG-19-007

- Two event topologies (ZZ_d and Z_dZ_d) are defined to maximize the sensitivity of searches
  - different selections are applied on these two topologies
- Irreducible backgrounds (ZZ, SM Higgs boson) are estimated by simulation, reducible background (Z+jets) are estimated from data
- No significant deviation from the standard model expectation is observed.





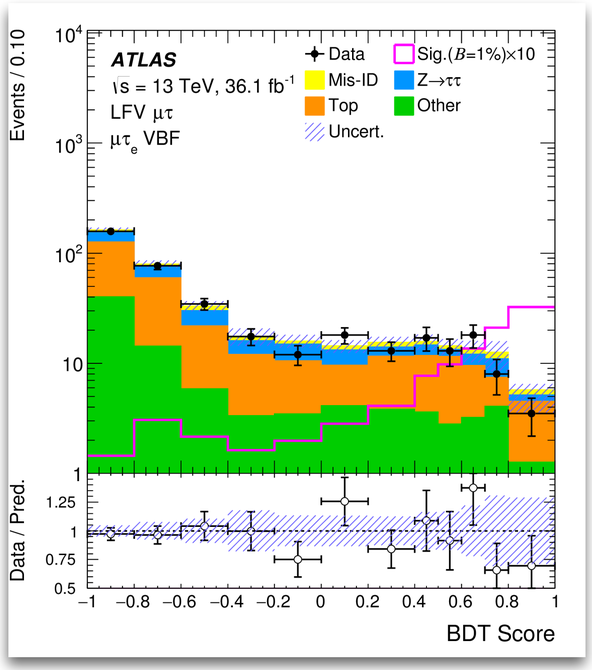


discontinuity due to the switch from experimentally to theory-driven

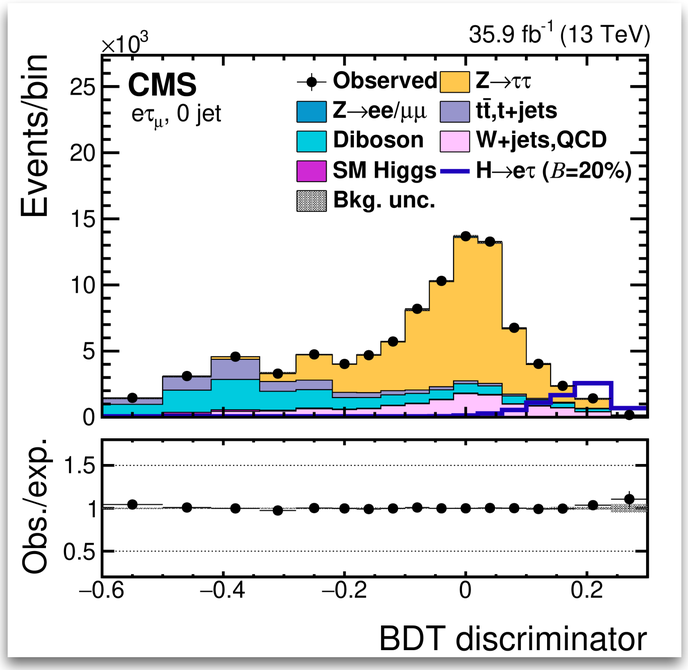
Lepton flavour violating

- **Lepton flavour violating decays** of the Higgs boson are **forbidden** in the **SM** but occur in many new physics scenarios.
- Both leptonic and hadronic decays of τ-leptons are considered in ATLAS and CMS, further categorization by using the number of jets.
  - events are further categorized into VBF and non-VBF categories.
- Same flavour lepton pairs are rejected to suppress Drell-Yan background.
- BDT classifiers are exploited in individual categories to enhance the signal separation from the background.

No significant excess is observed above the expected background from SM processes!



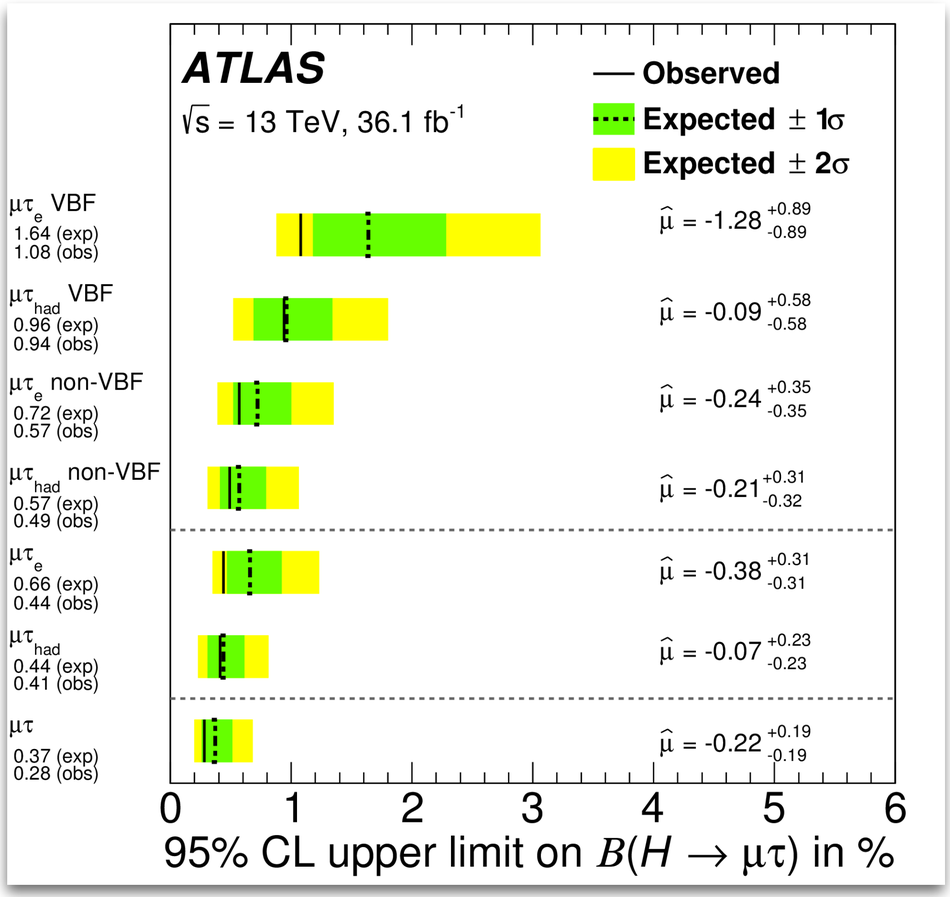
PLB 800 (2020) 135069



JHEP 06 (2018) 001

Lepton flavour violating h → μτ

ATLAS: B(h → μτ) < **0.28%**
$(0.37^{+0.14}\ _{-0.10}\ \%)$ at 95%CL



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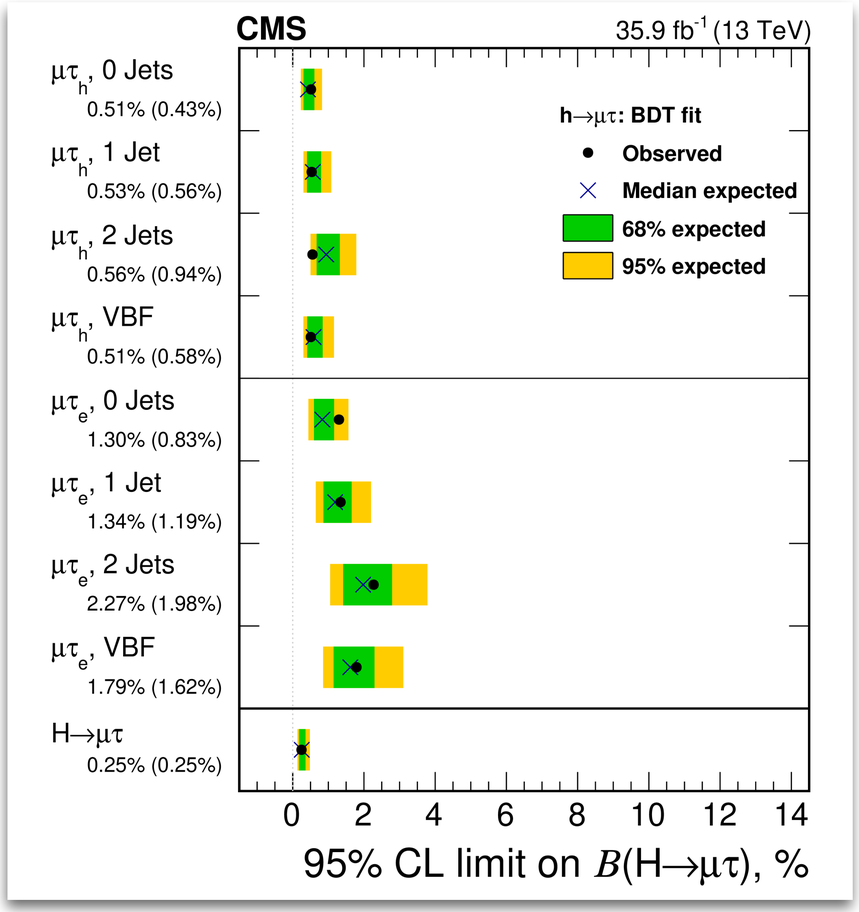
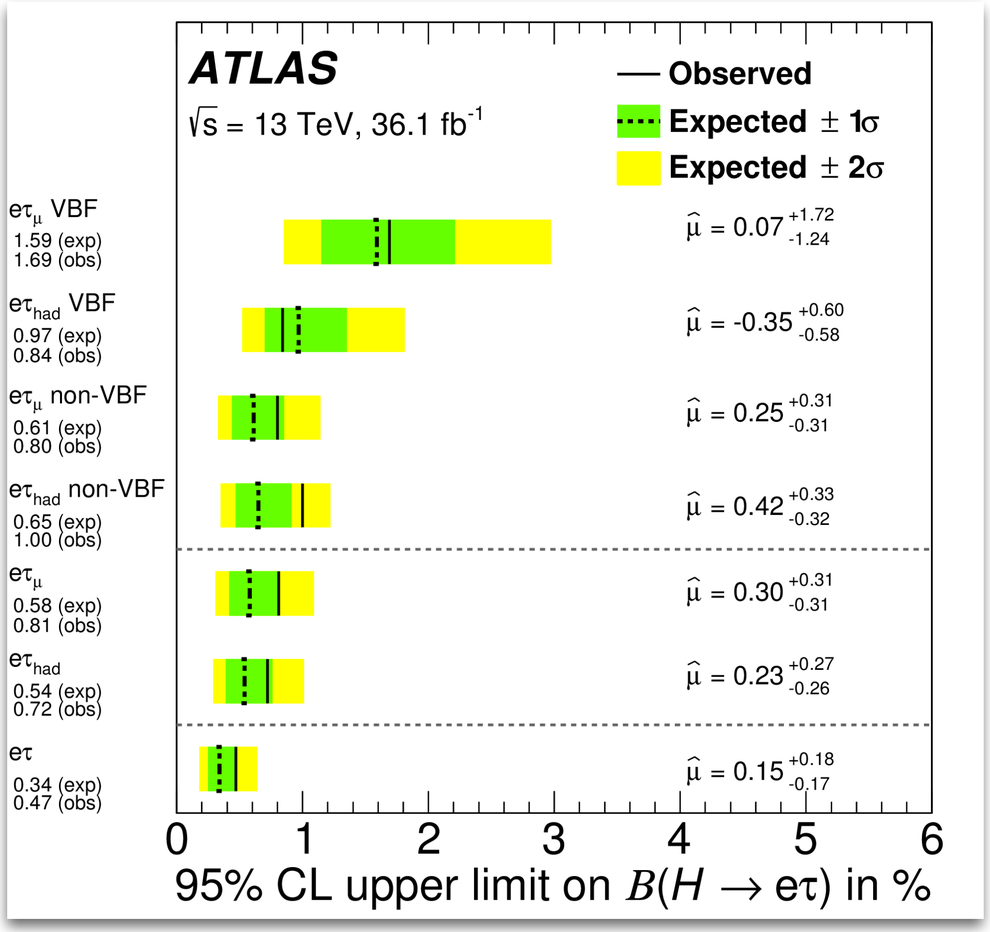
CMS: B(h → μτ) < **0.25%**
(0.25 %) at 95%CL



JHEP 06 (2018) 001

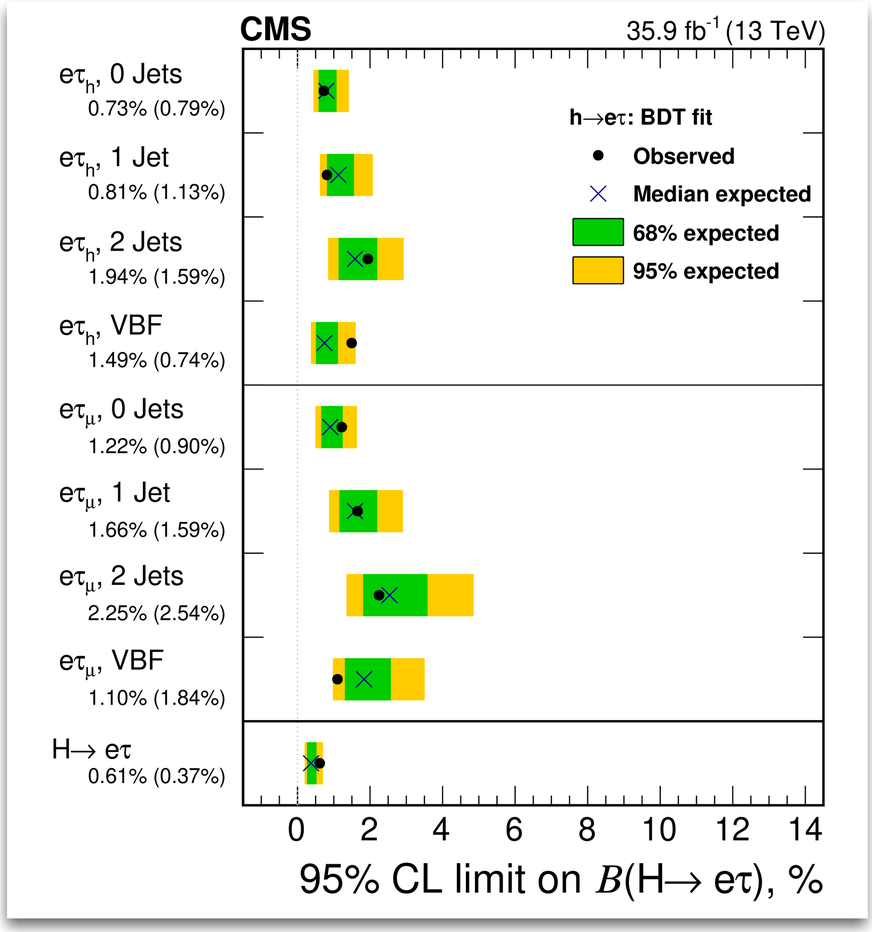
Lepton flavour violating h → eτ

ATLAS: B(h → eτ) < **0.47%**
$(0.34^{+0.13}{}_{-0.10}$ %) at 95%CL



PLB 800 (2020) 135069

CMS: B(h → eτ) < **0.61%**
(0.37 %) at 95%CL

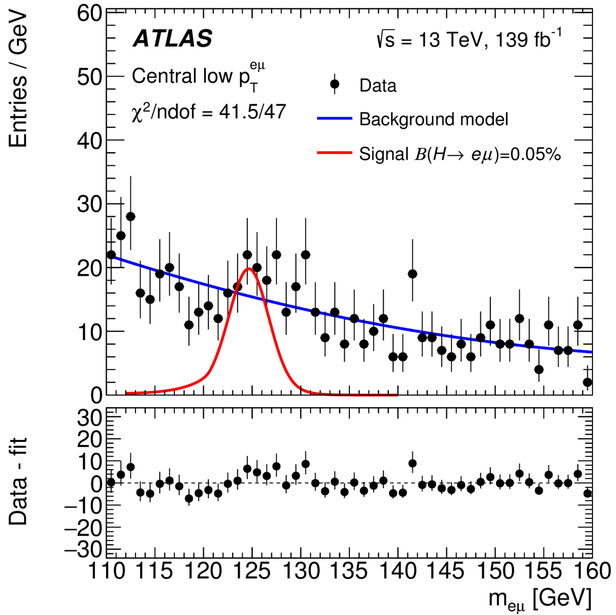


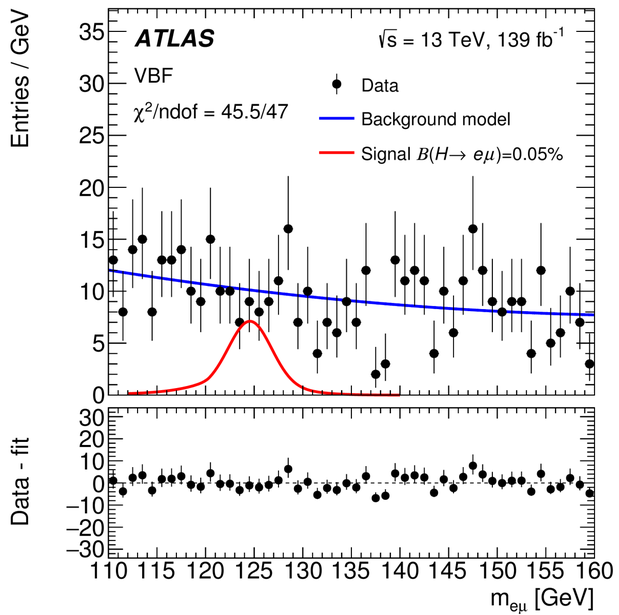
JHEP 06 (2018) 001

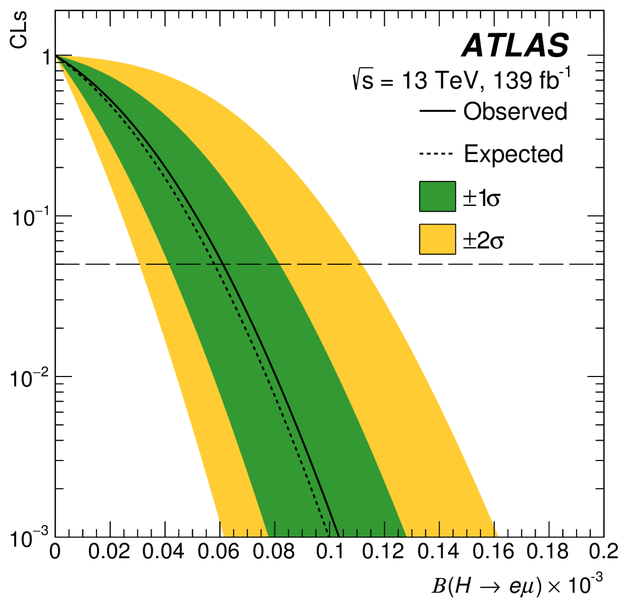
Lepton flavour violating h → eμ

PLB 801 (2020) 135148

- Eight categories differing in their expected S/B ratios are defined.
- Analytic functions are used to describe the $m_{e\mu}$ distributions for both the signal and the background.
- No evidence of the decay h → eμ is observed.
  - **ATLAS**: B(h → eμ) < 6.2x10^{-5} (5.9x10^{-5}) at 95%CL **@13TeV**
  - **CMS**: B(h→eμ) < 3.5x10^{-4} (4.8x10^{-4}) at 95% CL **@8TeV**

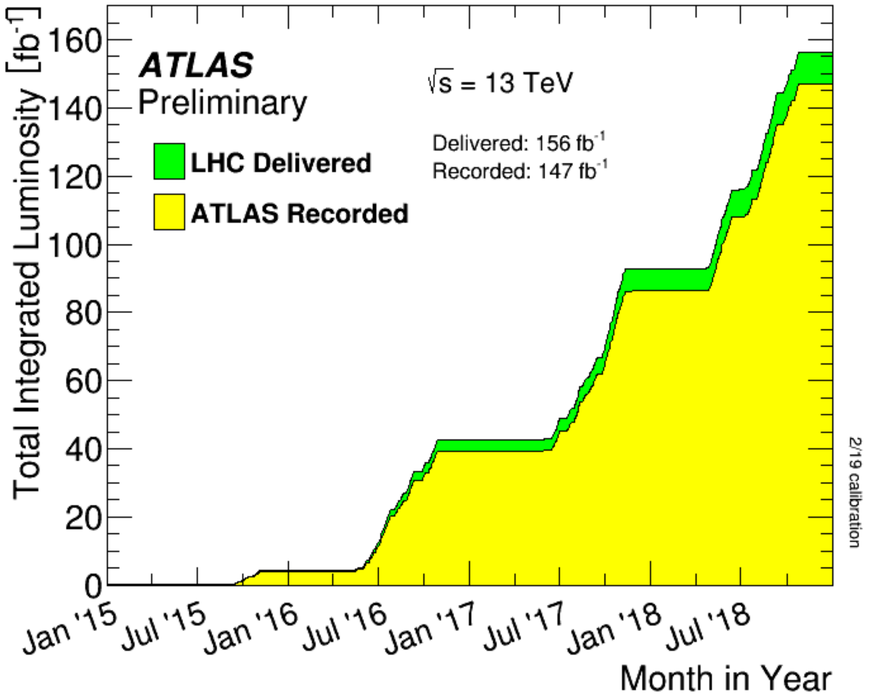


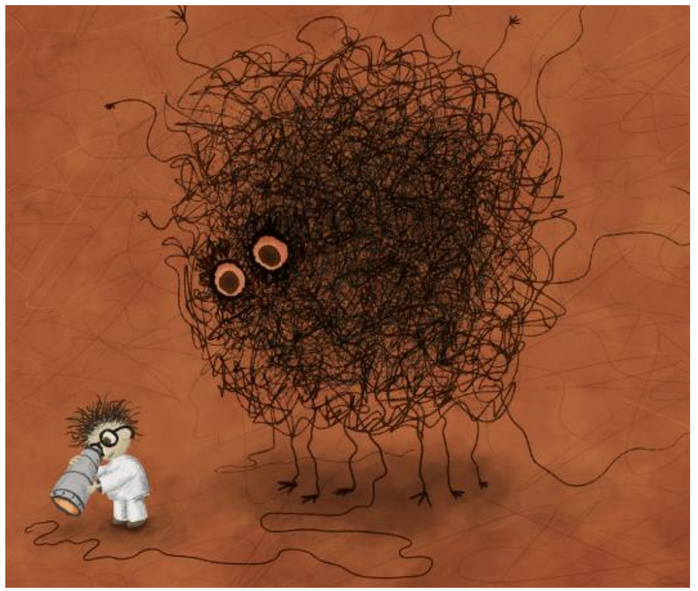




Conclusions

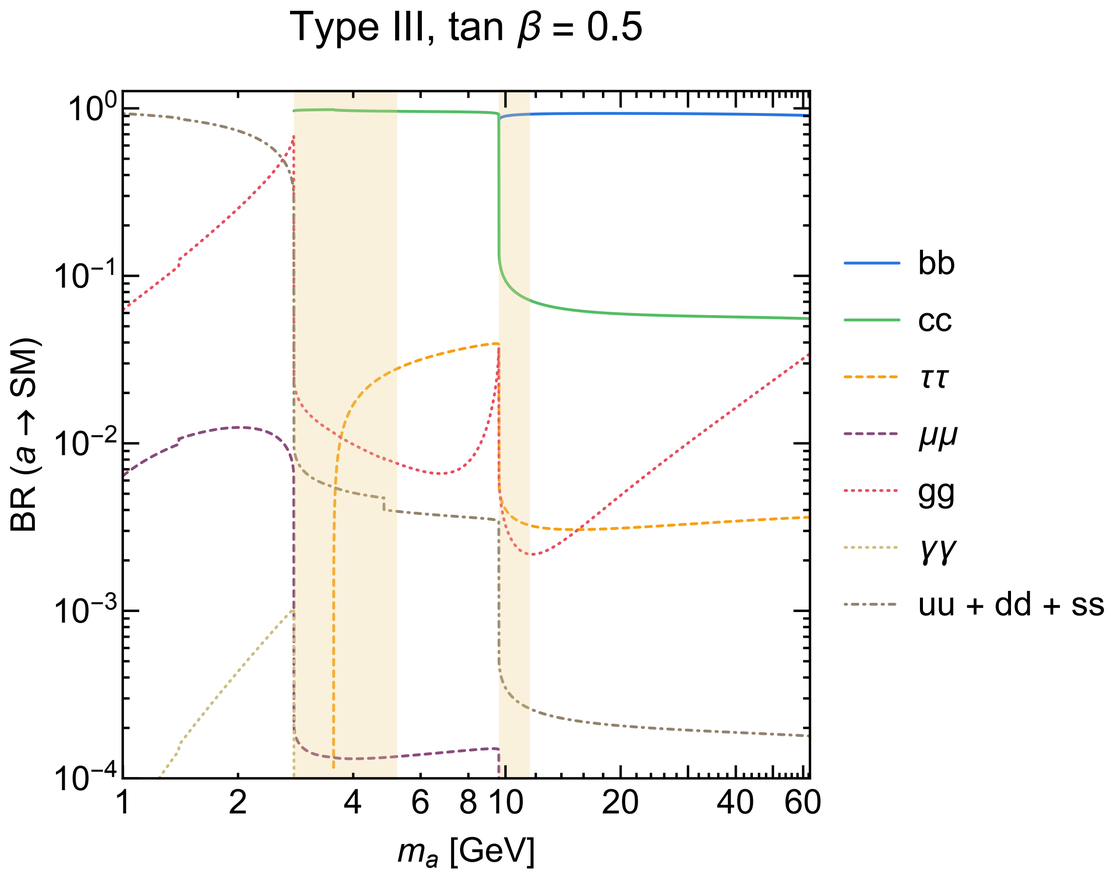
- The latest exotic Higgs boson decay searches in ATLAS and CMS are reported.
- No significant deviations yet observed from SM predictions.
- Looking forward to more results from ATLAS and CMS using the full Run-2 dataset!

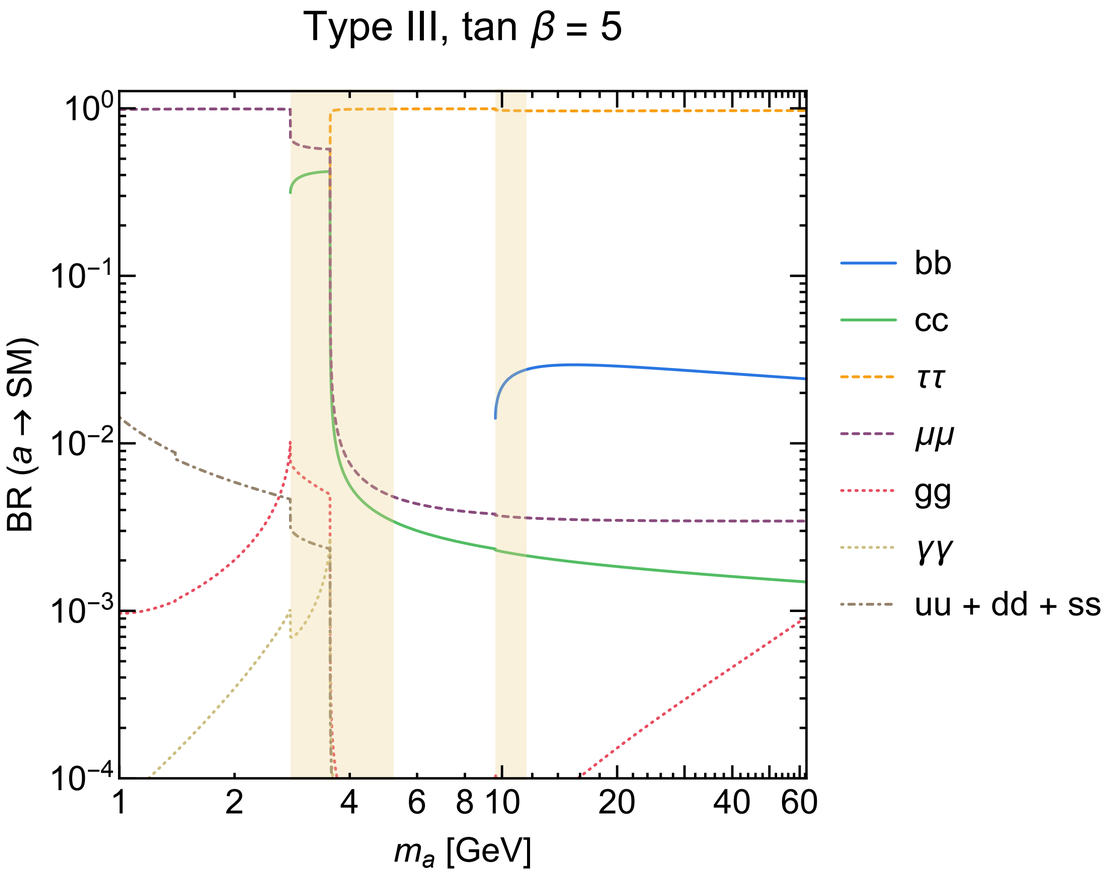




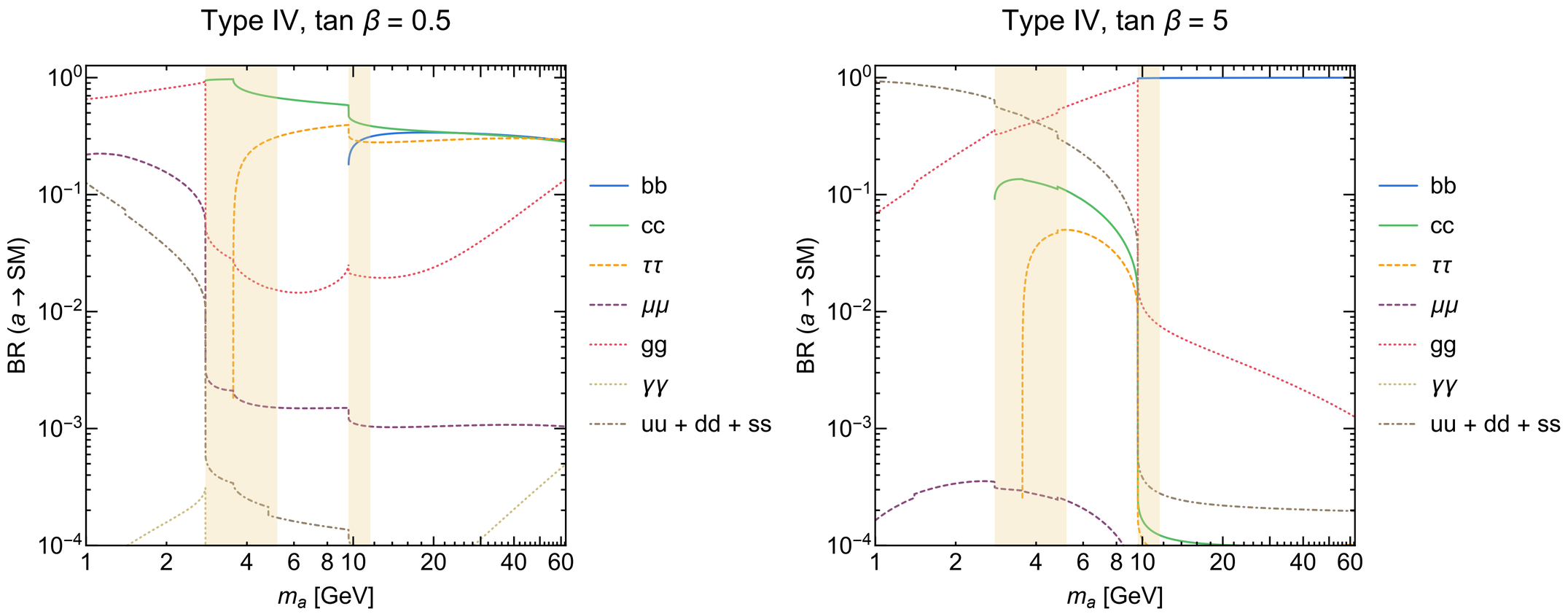
Thanks for your attention!

Two-Higgs-doublet model + one complex scalar singlet (2HDM+S)



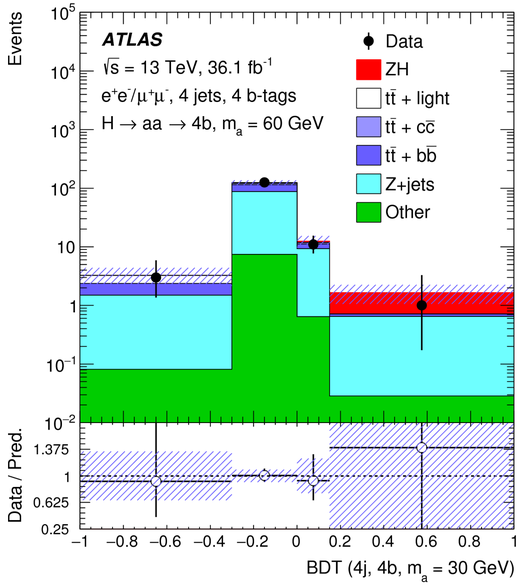


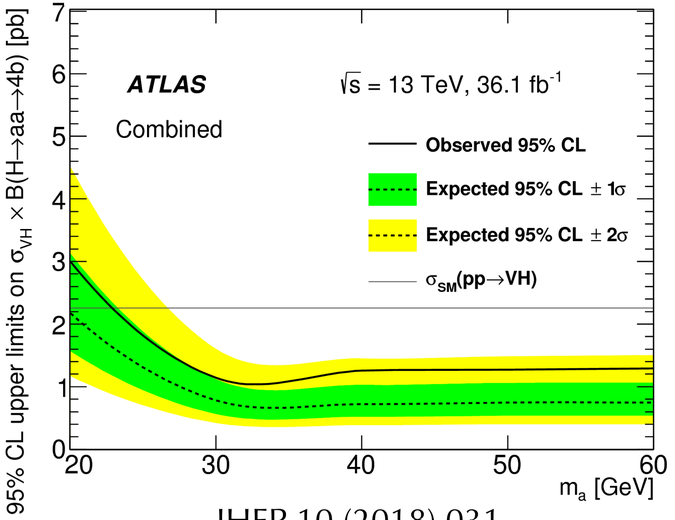
Two-Higgs-doublet model + one complex scalar singlet (2HDM+S)



Search for h→aa→4b

- In most of 2HDM+S models, B(a → bb) dominates in the range of ma > 10 GeV
- WH or ZH production with a single lepton or two leptons accompanied by a high multiplicity of b-tagged jets
- Consider mass of a-boson: **20 GeV ≤ m_a ≤ 60 GeV**
- Events are categorized into 7 CRs and 6 SRs according to the number of leptons, jets and b-tagged jets.
- A boosted decision tree (BDT) is trained in SRs
- 95%CL **obs**(exp) limits: σxB < **3.0** (2.2) pb @m_a=20 GeV, **1.3** (0.74) pb @m_a=60 GeV

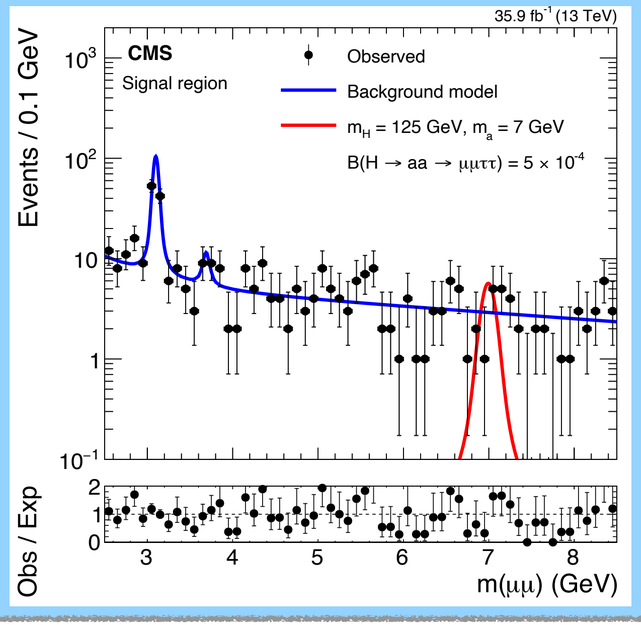




JHEP 10 (2018) 031

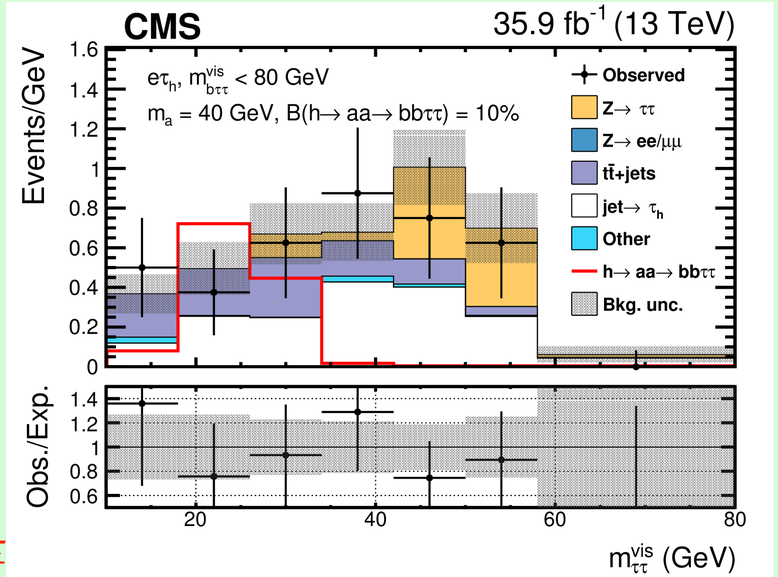
Search for h→aa→2μ2τ/2b2τ

- **3.6 GeV < m_a < 21 GeV**, the μμ and the ττ pairs have high Lorentz boost and are collimated.
- A special technique is developed for boosted τ lepton pair reconstruction (a → $\tau_\mu\tau_h$).
- The 2D fit of m(μμ) vs. m($\tau_\mu\tau_h$) is performed in data for background modeling and signal extraction within three m(μμ) ranges: [2.5,8.5], [6,14], and [11,25].



h→aa→2μ2τ

- **15 GeV < m_a < 60 GeV,** 3 channels: eμ, eτ_h, and μτ_h.
- Events are further separated into four categories with different signal-to-background ratios.
- The results of the search are extracted from a fit of the m(ττ) distributions in each of the categories

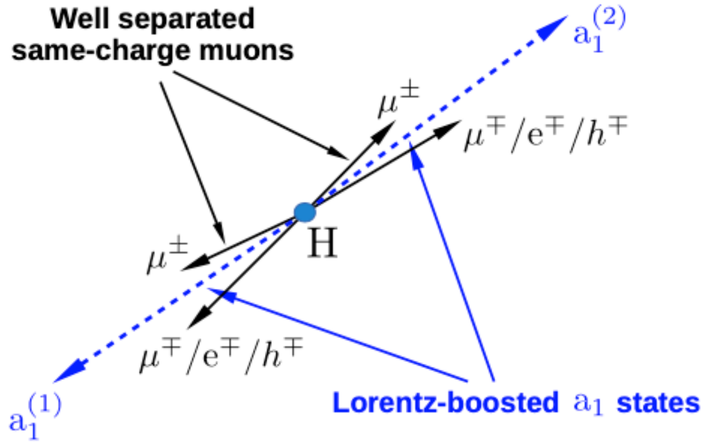


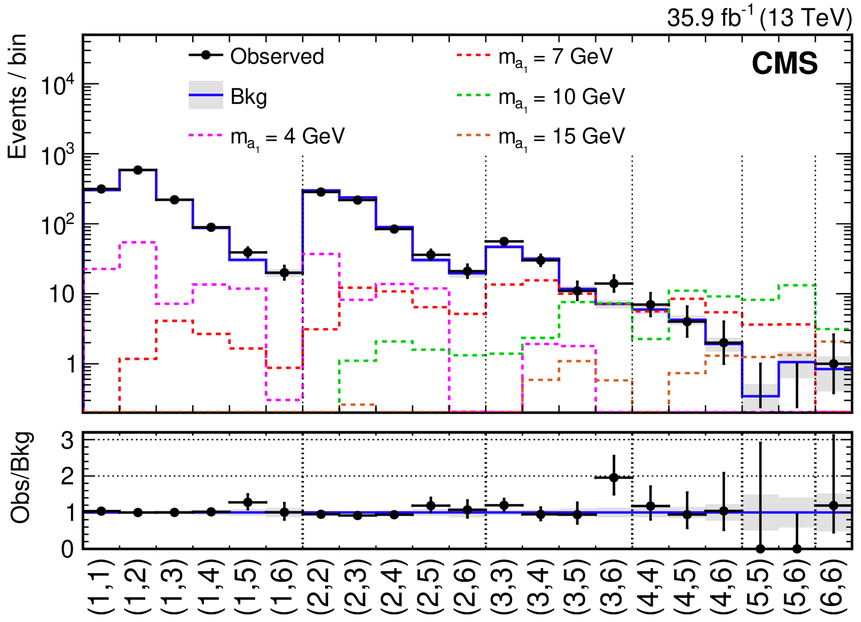
h→aa→2b2τ

Search for $h \rightarrow aa \rightarrow 4\tau/2\mu 2\tau$

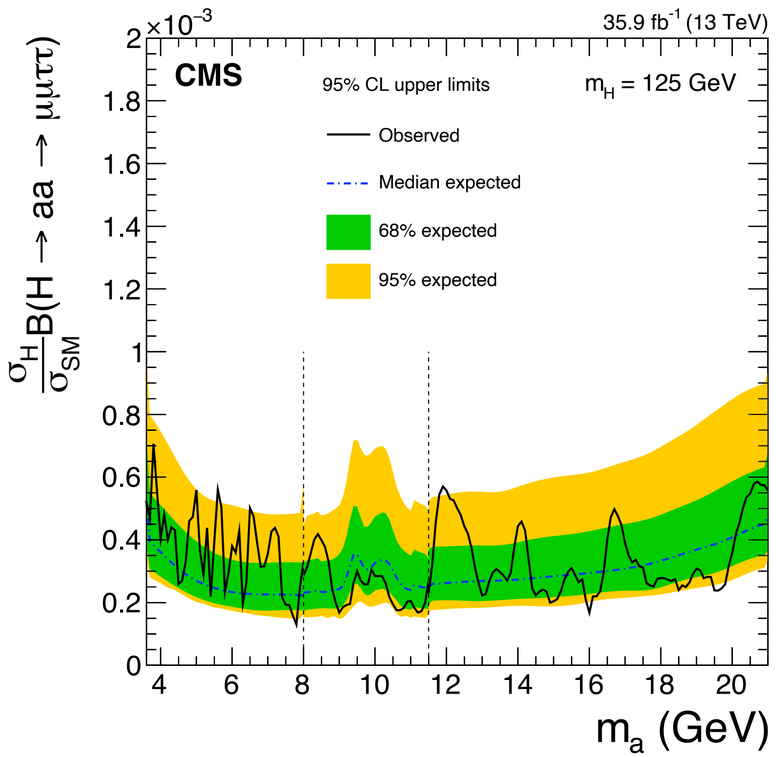
PLB 800 (2019) 135087

- **4 GeV < m_a < 15 GeV**, boosted scenario, decay products are collimated and fail the isolation selection criteria
  - *Special analysis strategy*: each a-boson is identified by the presence of a muon and only one additional charged particle
- Events are selected by using **same-charge (SC) dimuon systems** with large angular separation
- Backgrounds from the ttbar, Drell–Yan, and diboson production are largely suppressed by the SC muon requirement
- The signal is extracted with a binned maximum-likelihood fit applied to different (m_{a1},m_{a2}) regions

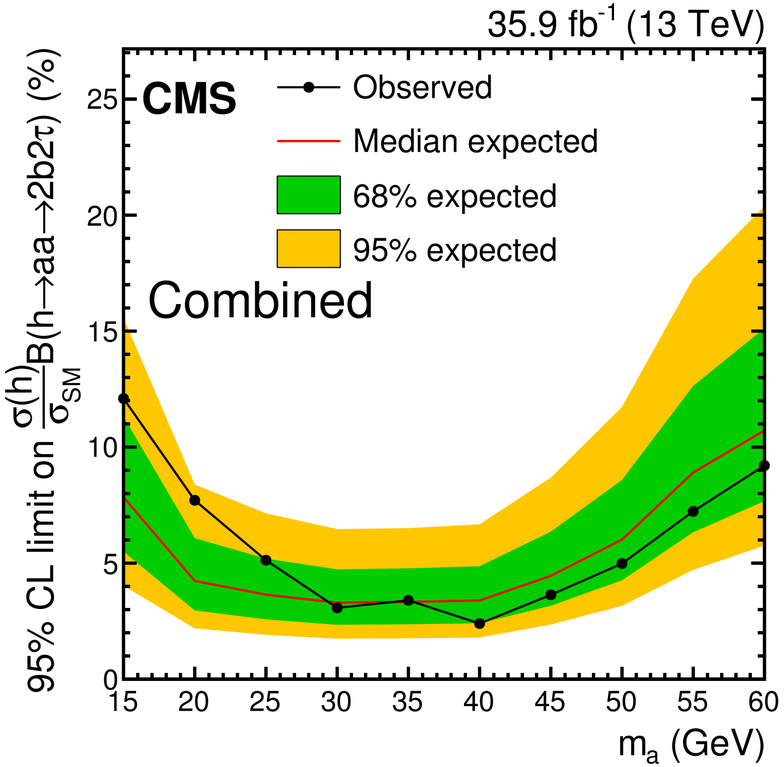




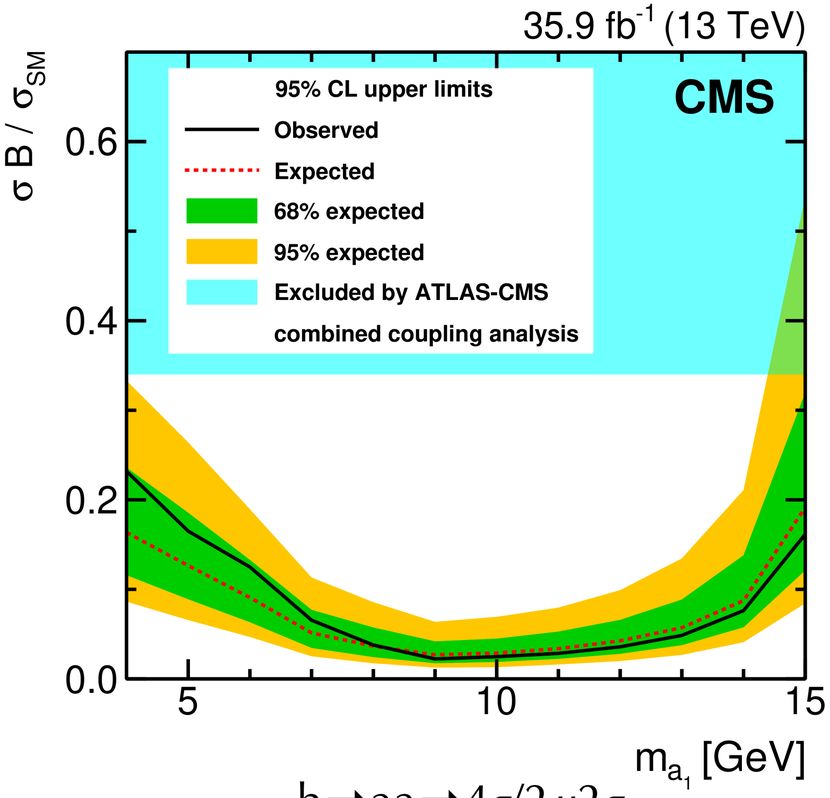
Search for h→aa→4τ/2b2τ/2μ2τ



h→aa→2μ2τ



h→aa→2b2τ

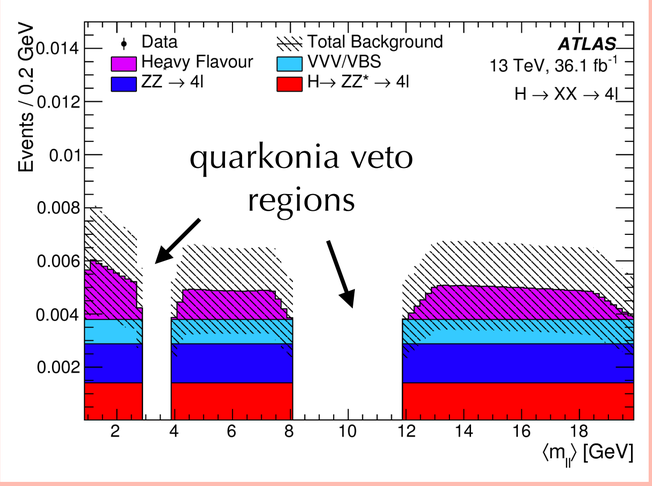


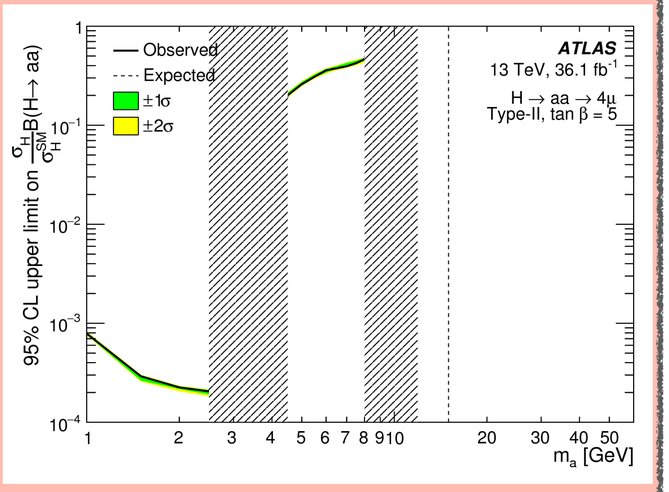
h→aa→4τ/2μ2τ

Search for h→aa→4μ in ggF production

- Searching for low mass a-bosons, it is more boosted and muons are less separated

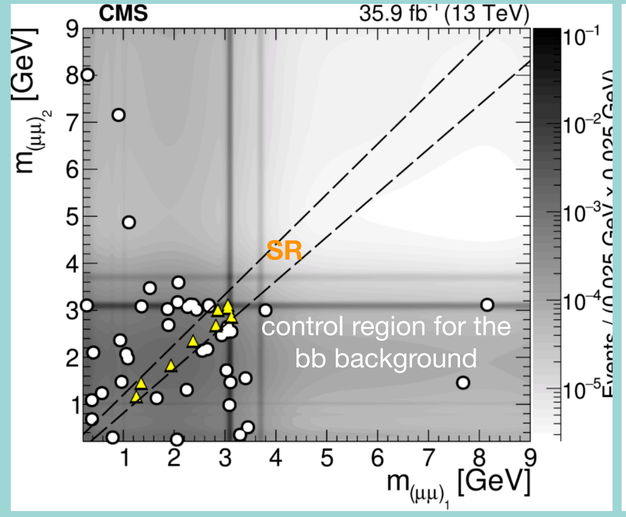
- **ATLAS**
  - 120 GeV < m_{4l} < 130 GeV, 0.88 GeV < $m_{12,34}$ < 20 GeV.
  - Events are vetoed if containing quarkonia resonances [J/Ψ, Ψ(2S), ϒ(1S), and ϒ(3S)]
  - Observed $(\sigma_H/\sigma_{SM})\times$ B(h → aa) upper limit @95%CL ~ **8×10^{-4}** for m_a=1GeV

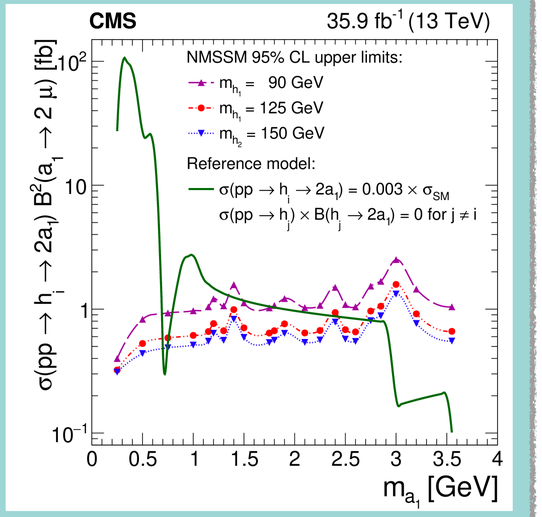




JHEP 06 (2018) 166

- **CMS**:
  - A two-dimensional template is constructed
  - Prompt double J/Ψ meson background is estimated from data, the electroweak background is negligible
  - 95%CL upper limits on **σxB < 0.15-0.39 fb** for **$0.25 < m_a < 8.5$ GeV**





Phys. Lett. B 796 (2019) 131