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Searches for Light Higgs Bosons

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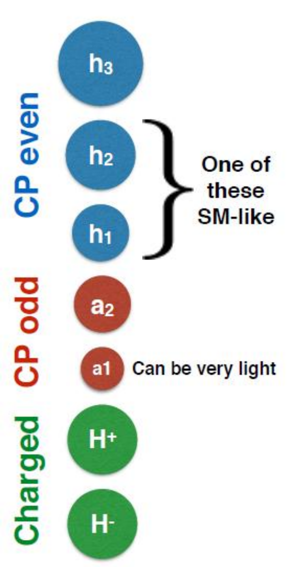
(for the CMS collaboration)

Outline – LHC Run 2 Results

Light Higgs Searches @

- $H(125) \rightarrow aa \rightarrow 4\mu$
- $H(125) \rightarrow aa \rightarrow 4\tau$
- $H(125) \rightarrow aa \rightarrow 2\mu 2\tau$
- $H(125) \rightarrow aa \rightarrow 2b2\tau$
- $H(125) \rightarrow aa \rightarrow 4\gamma$
- Light Scalar $\rightarrow \gamma\gamma$

Next-to-MSSM
(NMSSM)



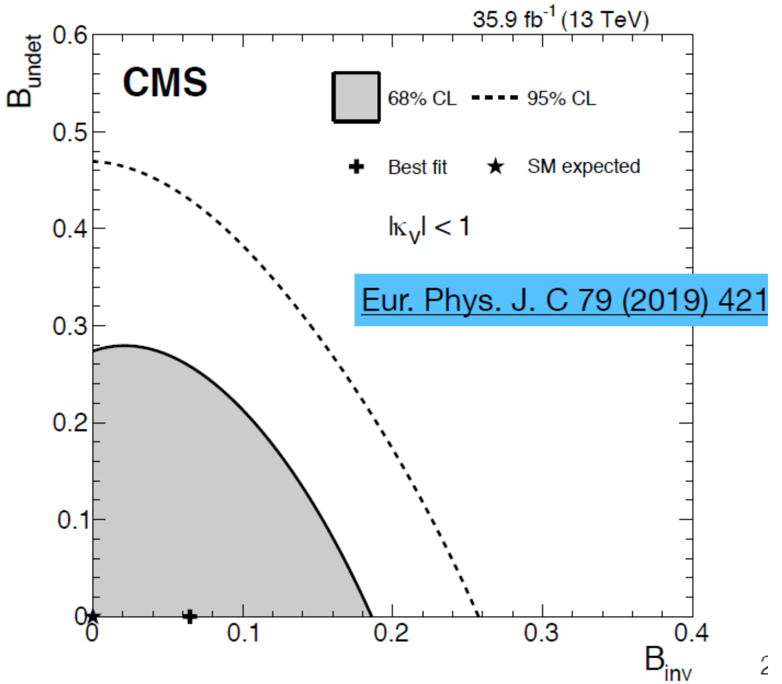
Light Higgs

- General Two Higgs Doublet Model (**2HDM**)
  - 2 Higgs Doublets ➡ 5 Higgs bosons: h, H, A, $H^{\pm}$
- Next-to-Minimal Supersymmetric Standard Model (**NMSSM**)
  - 2 Higgs Doublets + 1 singlet ➡ 7 Higgs bosons: h_1, h_2, h_3, a_1, a_2, $H^{\pm}$

- The **Higgs boson at 125 GeV** can be identified as the **next-to-lightest scalar**, allowing to envisage a possible **lighter particle**

BR of "a" boson to SM particles depends on

- **mass of the "a" boson**
- **models (types of the 2HDM)**
- **model parameters (tanβ)**



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Upper limits of branching ratio of H→invisible less than 22% at 95% CL

$$H(125) \rightarrow aa \rightarrow 4\mu$$

m_a mass: [0.25, 8.5] GeV

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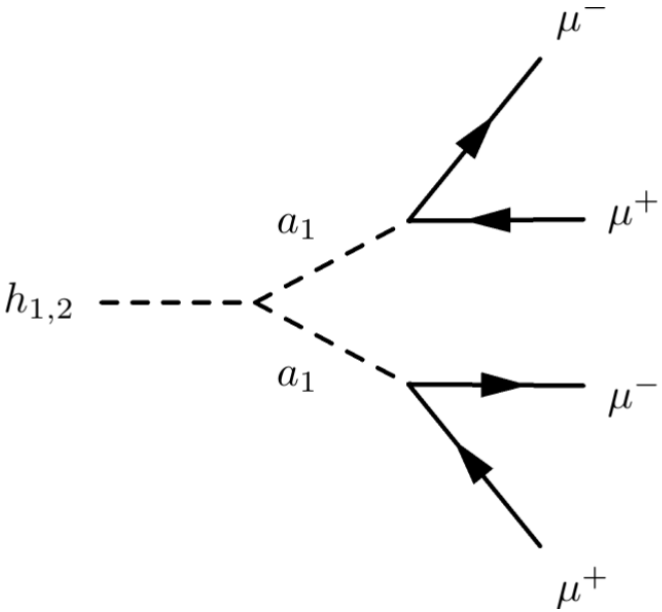


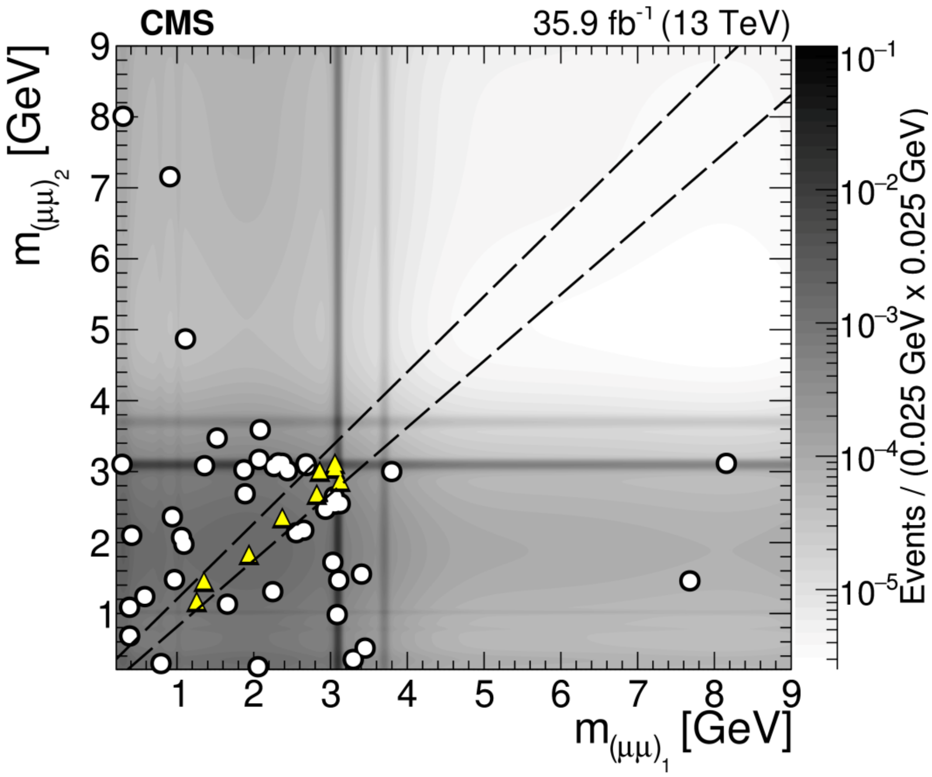
SM background dominated by:

bb production
in which both b-quarks decay to a pair of muons via double semi-leptonic decay or resonances

small contributions from:

electroweak production of four muons
such as qq→ZZ→4μ and qq→Z→2μ, the latter where a second Z is radiated and decays to a muon pair

direct J/ψ pairs
Irreducible background, two production mechanisms SPS and DPS. Estimated with a combination of data (control region) and MC simulation.



2D background template include all SM processes

Points represent the data surviving all selection except the invariant mass cut

Triangle: observed event on the border of signal region, i.e. about 5σ away from the exact diagonal

- 9 events are observed in signal region, with 7.95 ± 1.12 (stat) ± 1.45 (syst) events expected from SM backgrounds
- Upper limit at 95% CL on cross section times branching fraction times acceptance obtained for light boson masses in range **$2m_\mu < m_a < 2m_\tau$**

Model independent 95% CL upper limit on σ x BR to dimuons squared times acceptance set over the mass range **$0.25 < m_a < 8.5$ GeV** and found to vary between 0.15 and 0.39 fb

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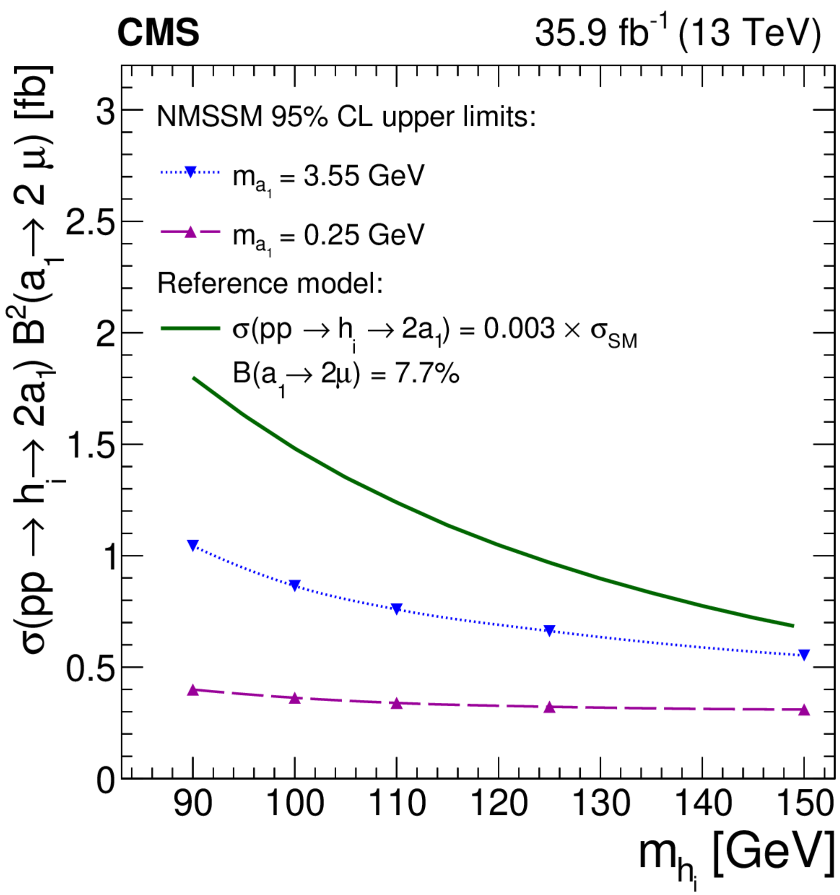
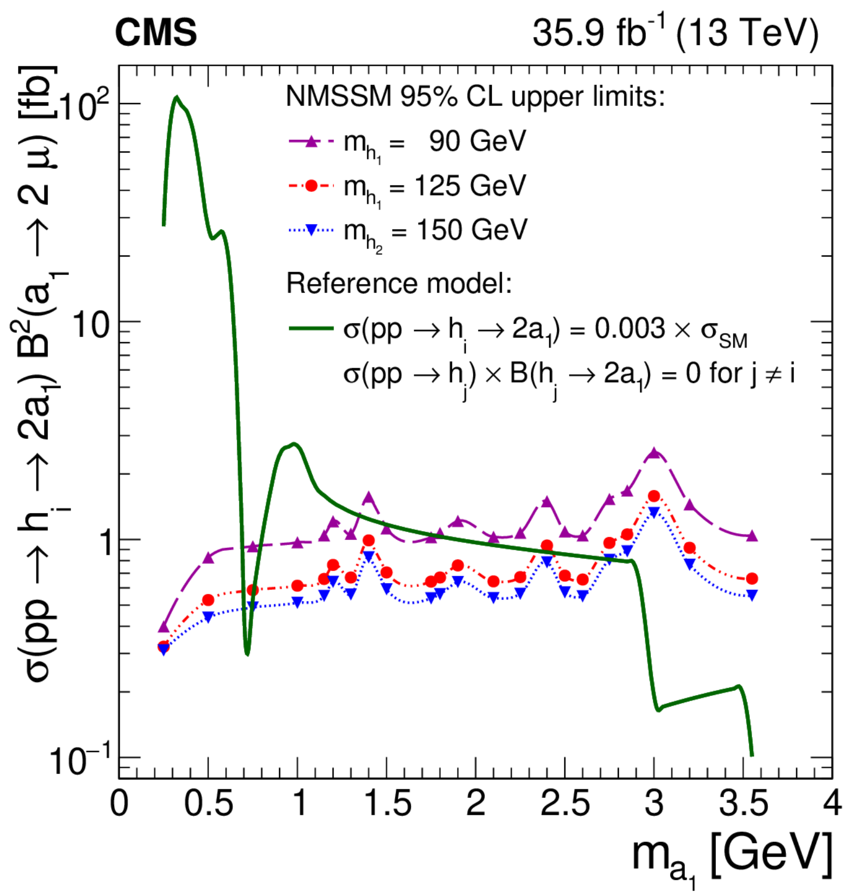
Results compared in the **NMSSM** scenario. Limits compared to a representative model (solid curve) using a simplified scenario





$H(125)\rightarrow aa\rightarrow \mathbf{4\tau}$

m_a mass: [3.6, 15] GeV

H(125) → aa→4τ

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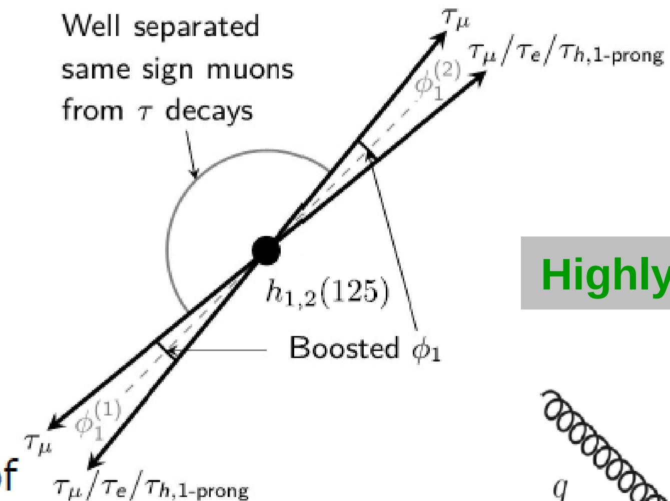
$gg \rightarrow h_{1,2}(125) \rightarrow 2\varphi_1 \rightarrow 4\tau$

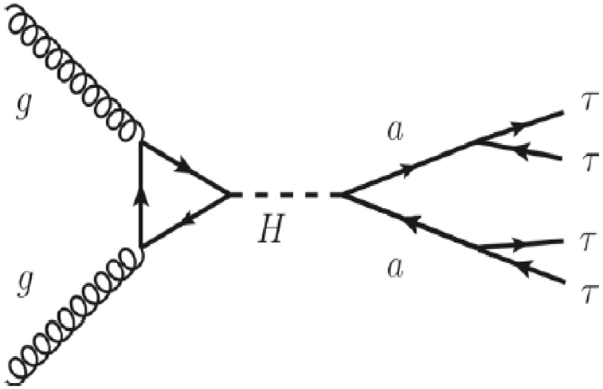
Probed masses of the φ_1 state:

$4\ \mathrm{GeV} < m_{\varphi 1} < 8\ \mathrm{GeV}$



considered decays of each φ_1 state : $\varphi_1 \rightarrow \tau_\mu + \tau_{\text{1-prong}}$

Highly Boosted Scenario

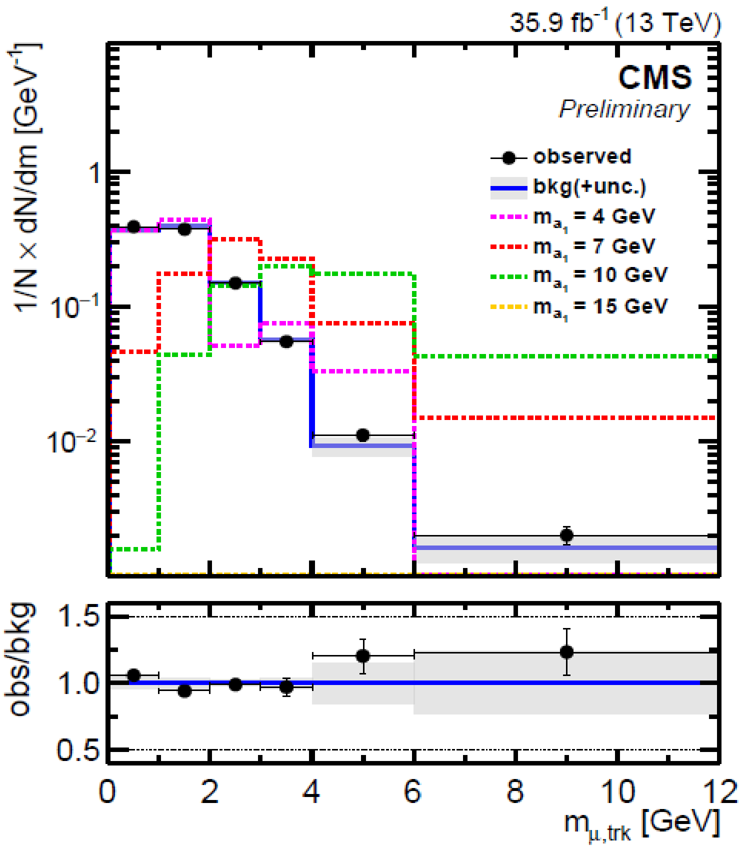


require two SS muons ($\mu^\pm\mu^\pm$) well separated in (η,φ) → suppression of QCD, EWK and top pair backgrounds

$m_{h(125)} \gg m_{\varphi 1} \rightarrow$ boosted φ_1

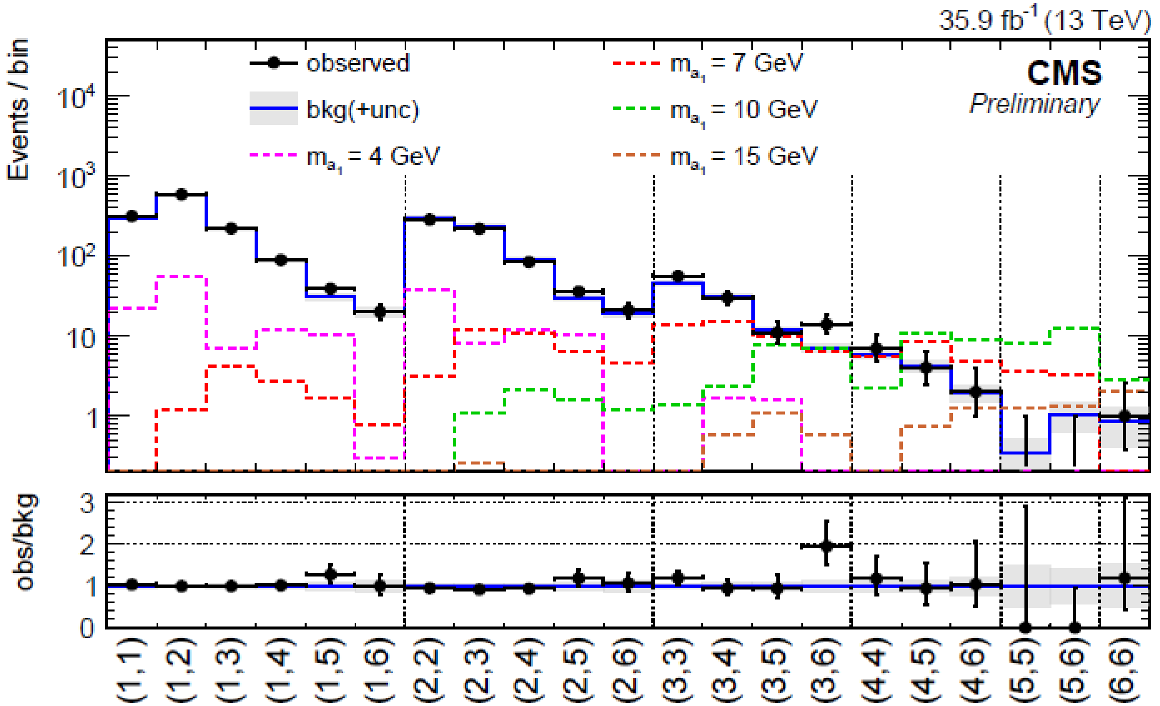
- small opening angle between muon and track from 1-prong tau decays
- require each muon to be accompanied by only 1 track (pt>2.5 GeV)

H(125) → aa→4τ



Normalized **invariant mass distribution** of the **muon-track system** for events passing the signal selection

The **QCD multijet background model** is derived from a control region with 2 or 3 soft tracks around the leading track



The unrolled 2D (m_1,m_2) in one row distribution used to extract the signal

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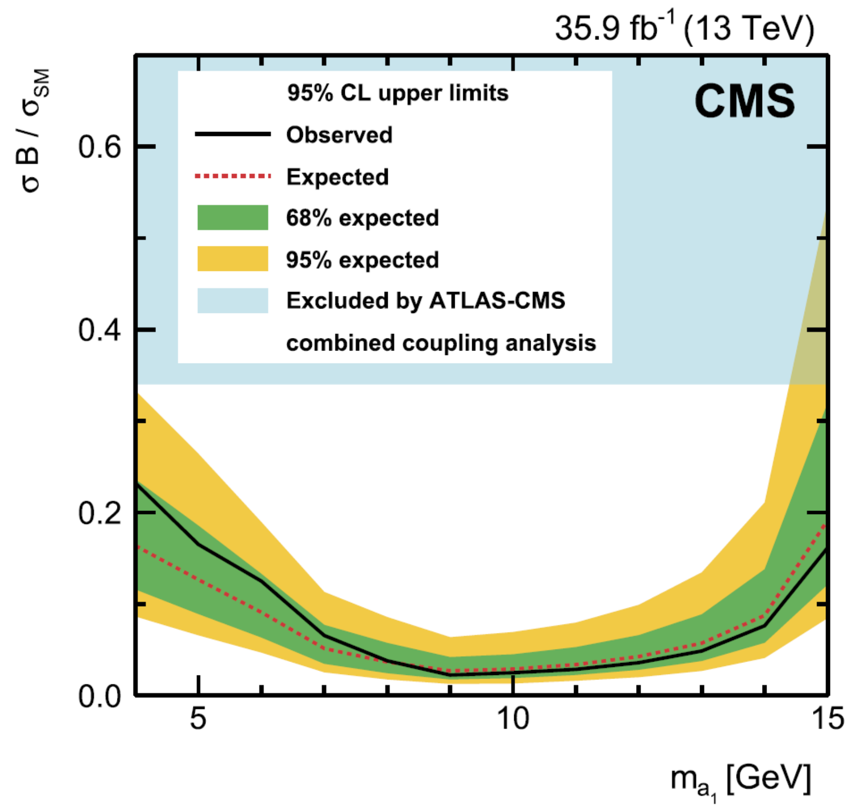
The distribution for the background is obtained after performing a maximum likelihood fit to the observed data under the background-only hypothesis

The signal normalization is computed assuming that the H(125) boson is produced in pp collisions with a rate predicted by the SM

No significant deviations of data from the background expectations are observed in the **unrolled 2D (m_1,m_2) distribution**



The observed and expected upper 95% confidence level limits on the signal cross section times the branching fraction

$\boldsymbol{\sigma(pp \rightarrow H(125) + X)\ .\ BR(H(125) \rightarrow a_1 a_1)\ .\ BR^2(a_1 \rightarrow \tau\tau)}$

relative to the inclusive Higgs boson production cross section $\boldsymbol{\sigma}_{SM}$ predicted in the SM

$$H(125) \rightarrow aa \rightarrow 2\mu 2\tau$$

m_a mass: [3.6, 21] GeV

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Invariant mass of four objects in the final state is below **100-130 GeV** or higher mass ranges: Compatibility with a **Higgs boson decay or heavy Higgs boson decay**

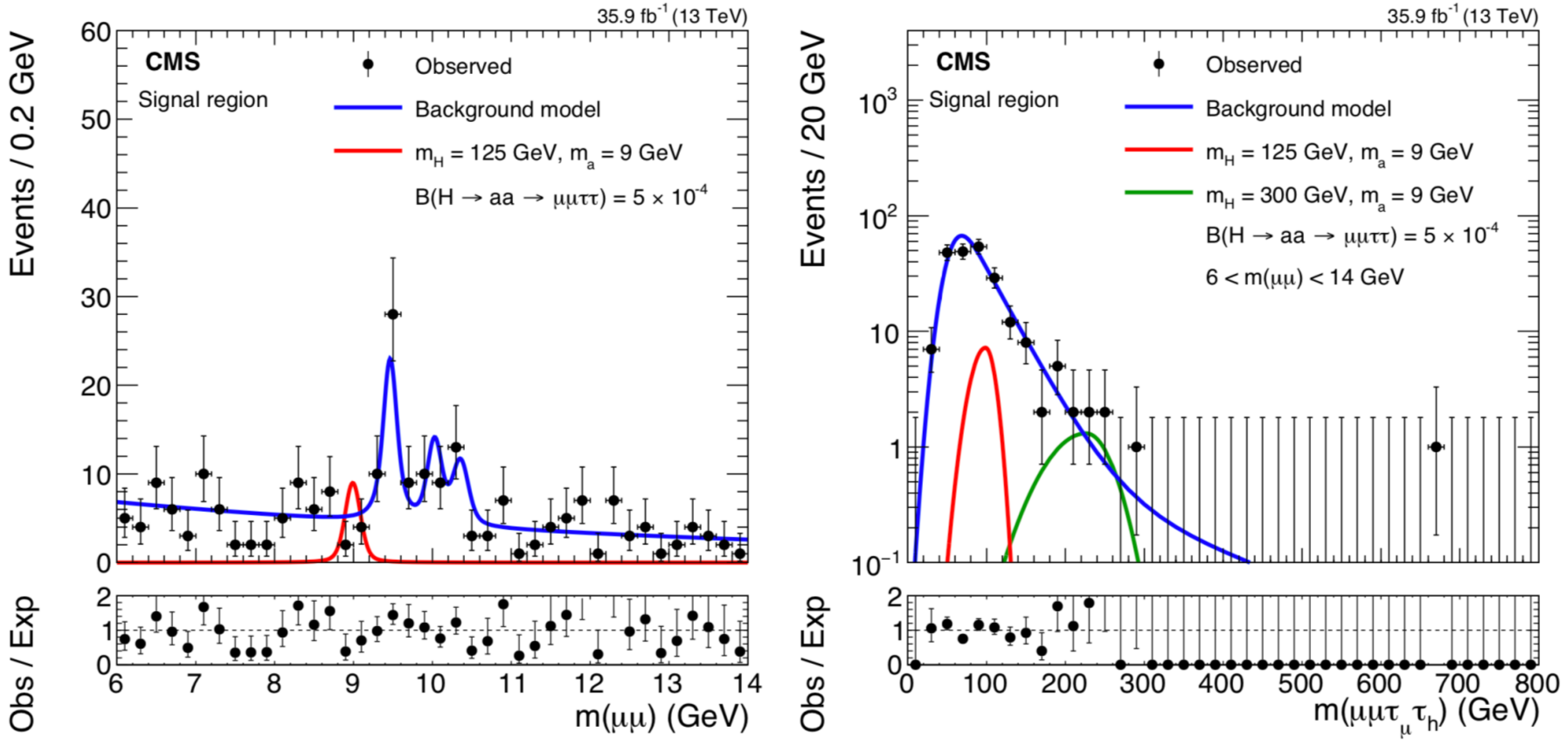
Pseudo-scalar boson mass range: [3.6, 21] GeV **Boosted muons and taus**
Final states with different **tau decay modes**: **$\mu\mu + \tau_\mu\tau_h$**

• In order to cope with boosted $\tau_\mu\tau_h$ pair topology, muons are cleaned from jets which seeds hadronic tau reconstruction
• The reconstructed τ_h can have 1 prong or 3 prongs (+ π^0 s)

Comparison:
✓ Standard tau reconstruction (τ_h HPS)
✓ Muon-Cleaned tau reconstruction ($\tau_\mu\tau_h$ HPS)

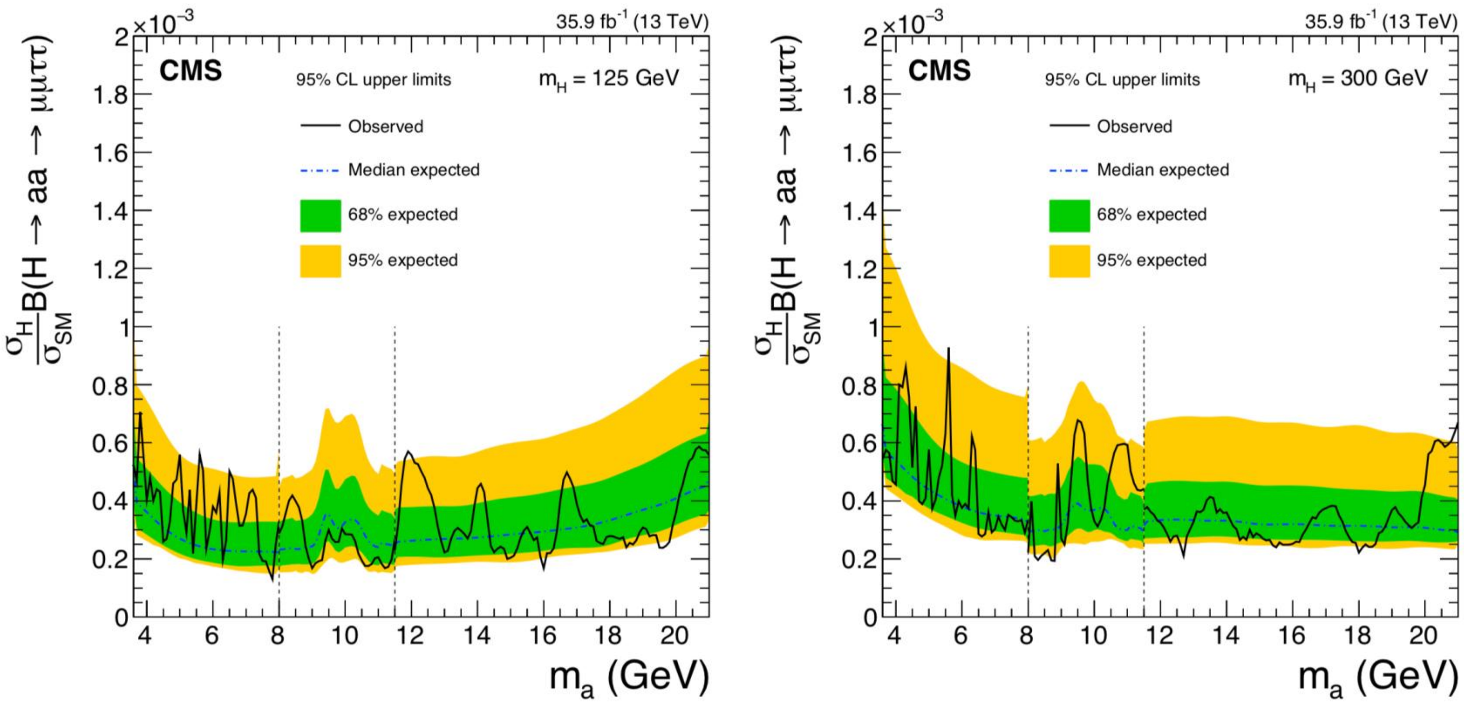
❑ Reduced efficiency at low a mass: Muon collinear with a charged hadron from tau
❑ Reduced efficiency at high a mass: Large separation between muon and tau while the requirement of the boost topology

H(125)→aa→2μ2τ



- The dominant background is Drell-Yan μμ + jet(s)
- Parametrized signal & background distribution: Perform a 2D **unbinned maximum likelihood fit**
- Use a polynomial function to interpolate between the generated masses
- Variables used for simultaneous fit: **Di-muon mass and Four body visible mass ($\mu\mu\tau_\mu\tau_h$)**

H(125)→aa→2μ2τ



- ❑ First model independent limits set in heavy Higgs boson mass (300 GeV) for H → aa in 95% CLs
- ❑ The three peaks in the middle are due to the influence of upsilon resonances
- ❑ The dominant uncertainty is from the background model around upsilon resonances (5-20%)

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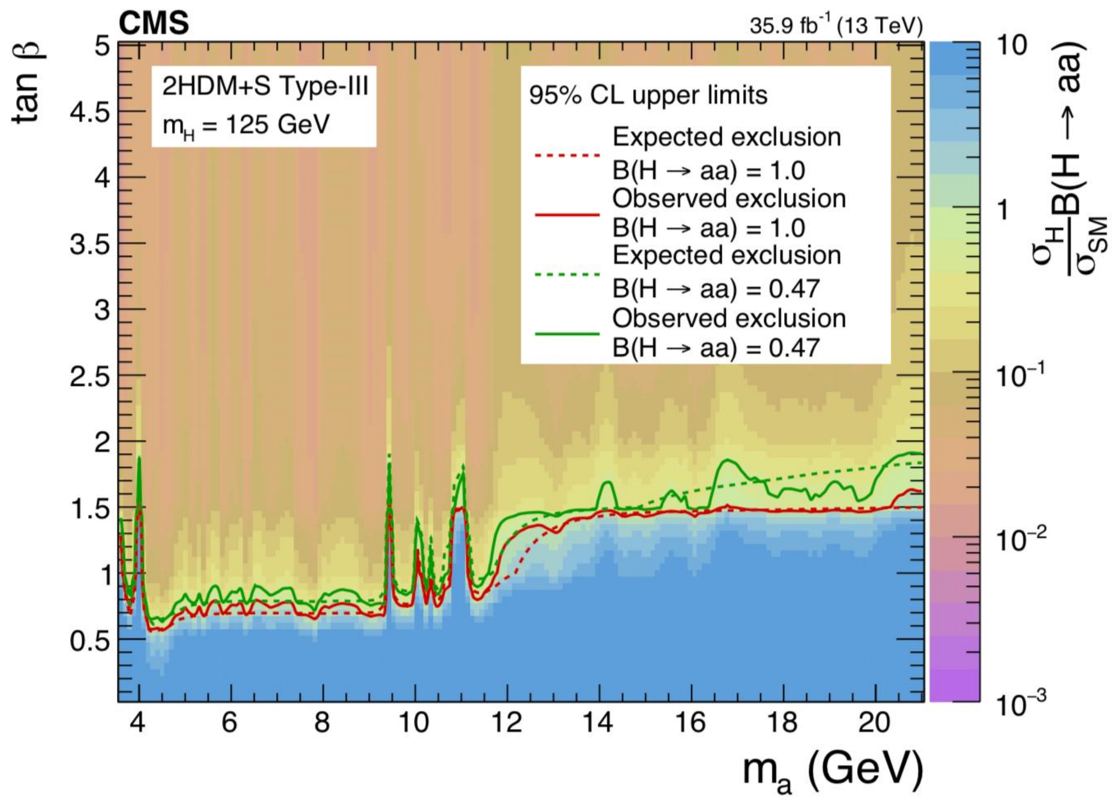
- ❑ When the ‘a’ boson mass is below the b-quark pair threshold:
- ✓ Upper limits on B(H → aa) are stronger than the 0.47 inferred from combined measurements of SM Higgs couplings for tan $\beta \geq$ 0.8-0.9
- ✓ Upper limits become as strong as 10% for tan $\beta \geq 1.5$



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In **2HDM+S Type-III** models, the predicted branching fraction to leptons increases with tan β, leading to strong upper limits for pseudoscalar boson masses tested when tan $\beta \geq 1.5$

$H(125)\to aa\to 2\mu 2\tau$

m_a mass: [15, 62.5] GeV

JHEP 11 (2018) 018

- Events are selected only if the invariant mass of the four objects in the final state is below 100 - 130 GeV

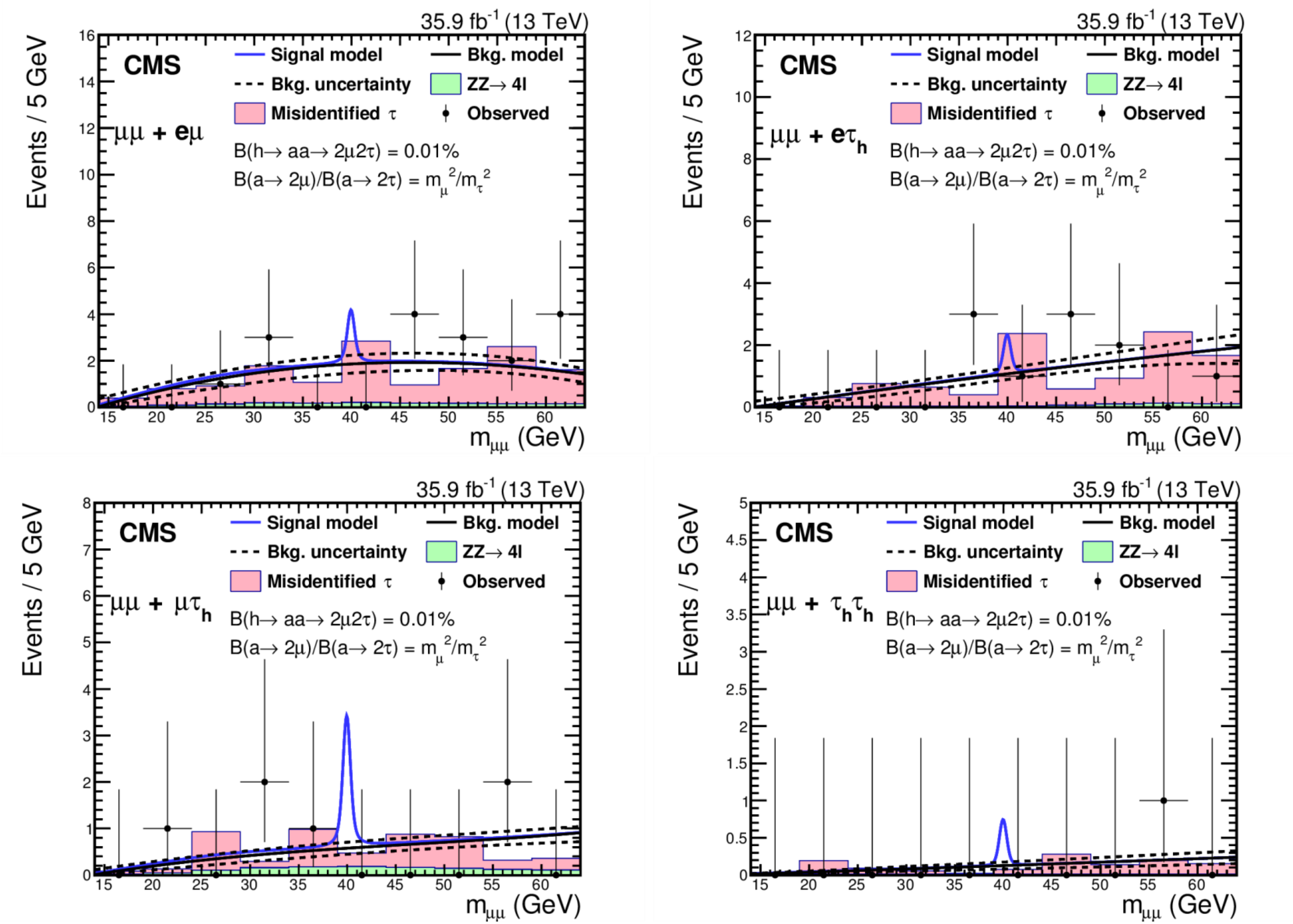
- 4 final states scenarios studied: **$\mu\mu \times (e\mu, e\tau_h, \mu\tau_h, \tau_h\tau_h)$**

- Requires 4 well reconstructed and isolated leptons

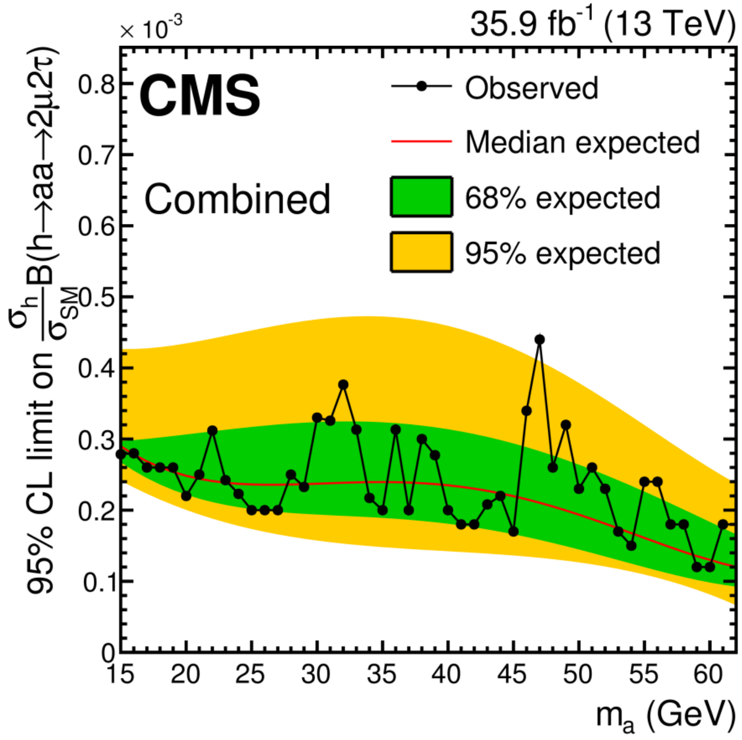
- Main backgrounds (fake leptons or taus) estimated from data mostly **Z + jets** and **WZ + jets** events
  - **shape** obtained from data in signal and ZZ background free control region with τ_h candidates of same sign (SS), τ_h isolation relaxed
  - **yield** is estimated from data events that have one or two non-isolated τ_h
  - background estimation method has been validated in simulation for WZ + jets and Z + jets

- Final observable to probe presence of signal is the **dimuon mass distribution**
  - Dimuon mass distributions of the simulated $H(125) \to aa \to 2\mu 2\tau$ signal events passing all selection criteria are parameterized with Voigt functions

H(125)→aa→2μ2τ

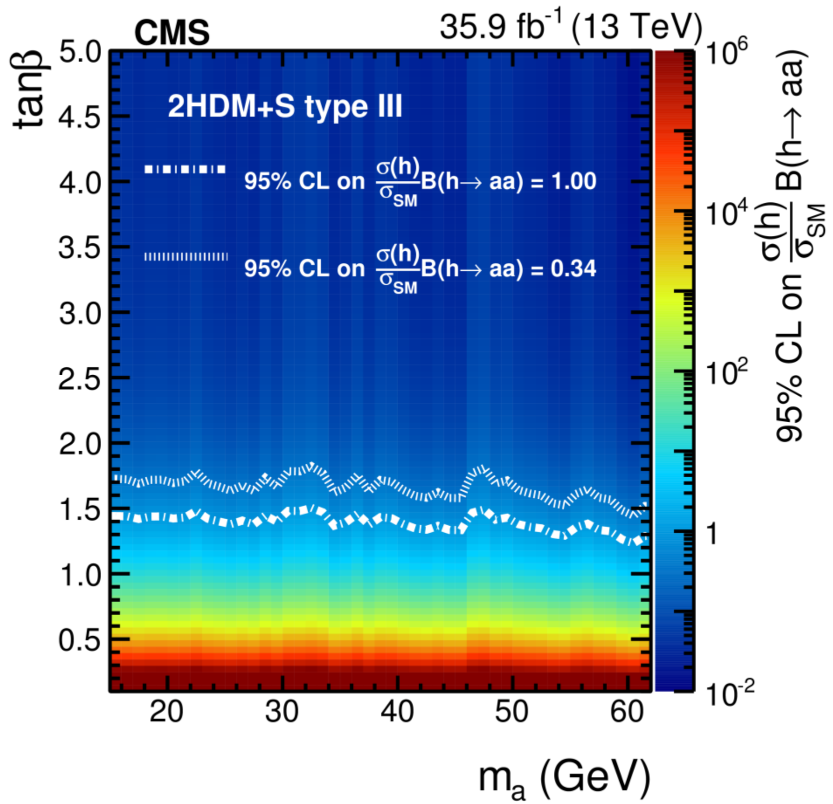


35.9 fb-1 (13 TeV)
CMS
Signal model
Bkg. model
Bkg. uncertainty
ZZ→ 4l
Misidentified τ
Observed
μμ + eμ
μμ + eτh
μμ + μτh
μμ + τhτh
B(h→ aa→ 2μ2τ) = 0.01%
B(a→ 2μ)/B(a→ 2τ) = mμ2/mτ2
Events / 5 GeV
mμμ (GeV)



JHEP 11 (2018) 018

Most stringent limits are obtained in **2HDM+S type III** at large tanβ, where couplings to leptons are enhanced



Maximum-likelihood fit to the **dimuon invariant mass** distribution is performed

No significant excess observed above expected backgrounds in $\mathbf{m_{\mu\mu}}$ range from **15** to **62.5 GeV**

Upper limits on BR(H→aa→2μ2τ) relative to SM Higgs production as low as **$1.2\text{x}10^{-4}$** for **m_a=60 GeV**

$$H(125) \rightarrow aa \rightarrow 2b2\tau$$

m_a mass: [15, 62.5] GeV

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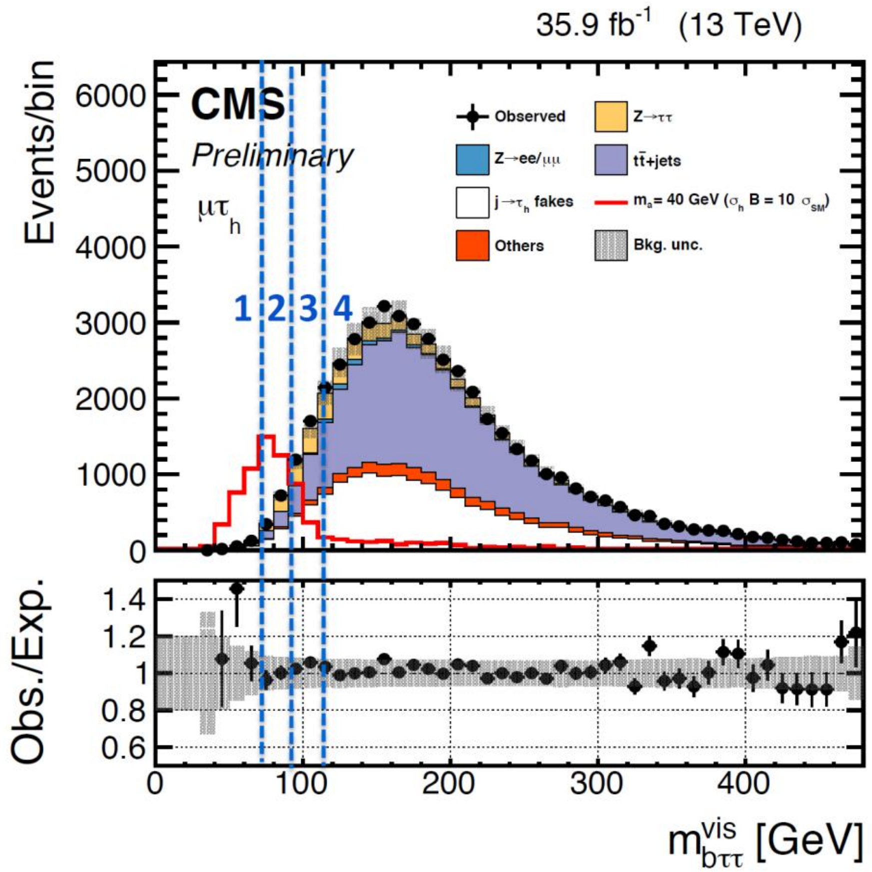
3 tau pair final states investigated: **$e\tau_h$, $\mu\tau_h$, $e\mu$**

- $\tau_h\tau_h$ discarded because of high trigger thresholds, ee and μμ discarded because of low BR and large backgrounds
- At least **1 b-tagged jet** (p_T>20 GeV) in addition to the leptons:
- Most signal events only have one b-tagged jet because the generated b-jets are too soft



- Visible invariant mass of tau pair and b-jet less than 125 GeV as neutrinos in τ decays and soft b-jets not reconstructed
- 4 categories based on $m_{b\tau\tau}$

H(125)→aa→2b2τ

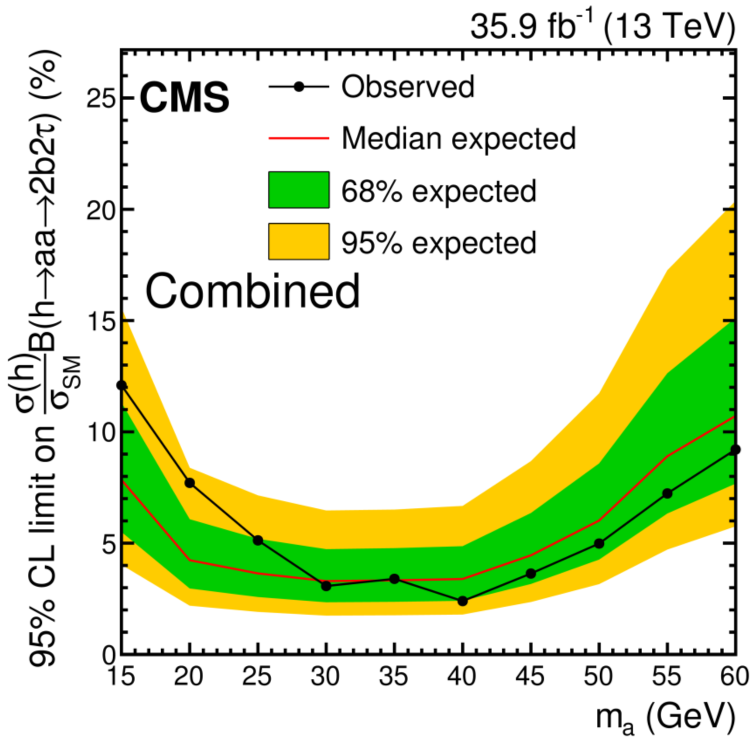
Low $m_{b\tau\tau}$ categories with smaller background
Highest $m_{b\tau\tau}$ category maximum background used as control region

Thresholds on kinematic cuts depend on the final state and category

Lowest $m_{b\tau\tau}$ category is the most sensitive with smallest background contribution

Results extracted by fits to di-tau visible mass distributions (to peak below m_a)

Uncertainties include e/μ, τ_h and b-jet identification, τ_h energy scale, Z→ll bkg, jet→ τ_h fakes bkg and top quark pair bkg (normalisation), Z→ττ shape



H(125)→aa→2b2τ

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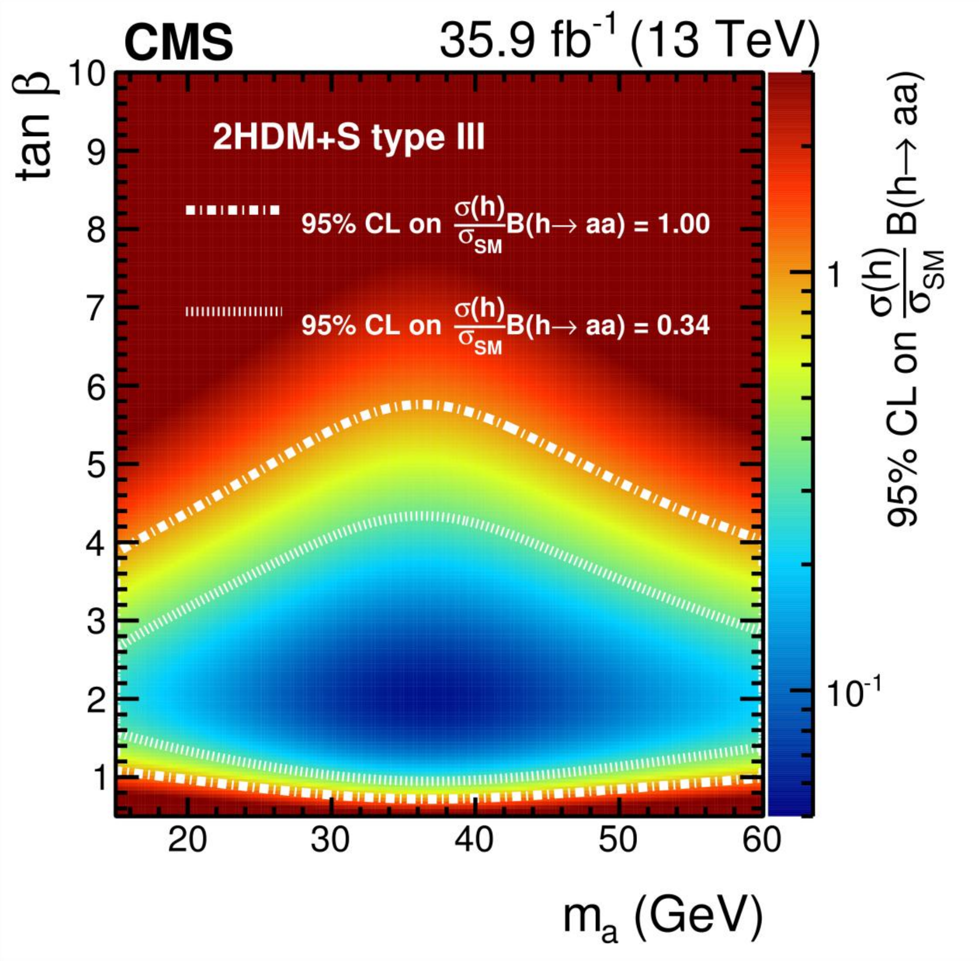
First time H(125)→aa→2b2τ decays are probed:
Large branching fraction (heavy b and τ mass),
and possible to trigger in ggF production

No significant excess of events observed

In the NMSSM, BR(h→aa)>23% excluded at 95% CL for m_a~ 35 GeV

Limits improved by several factors in the mass region 25 GeV < m_a < 62.5 GeV, and by more than an order of magnitude in 15 GeV < m_a < 25 GeV

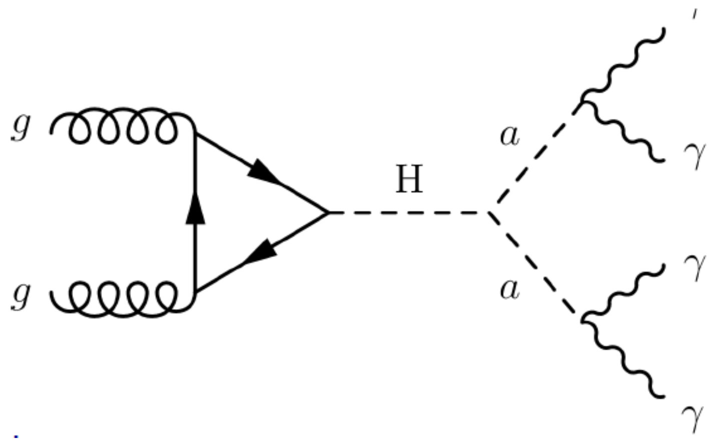


$$H(125) \rightarrow aa \rightarrow \gamma\gamma$$

m_a mass: [15, 60] GeV

Search for **4 isolated photons**, in the **mass range**
15 GeV < m_a < 60 GeV

- ❑ In some models BR($a \to \gamma\gamma$) is large
- ❑ Low background
- ❑ A BDT classifier is trained to distinguish signal from 4γ background
- \- Parameterized as function of the hypothesised m_a

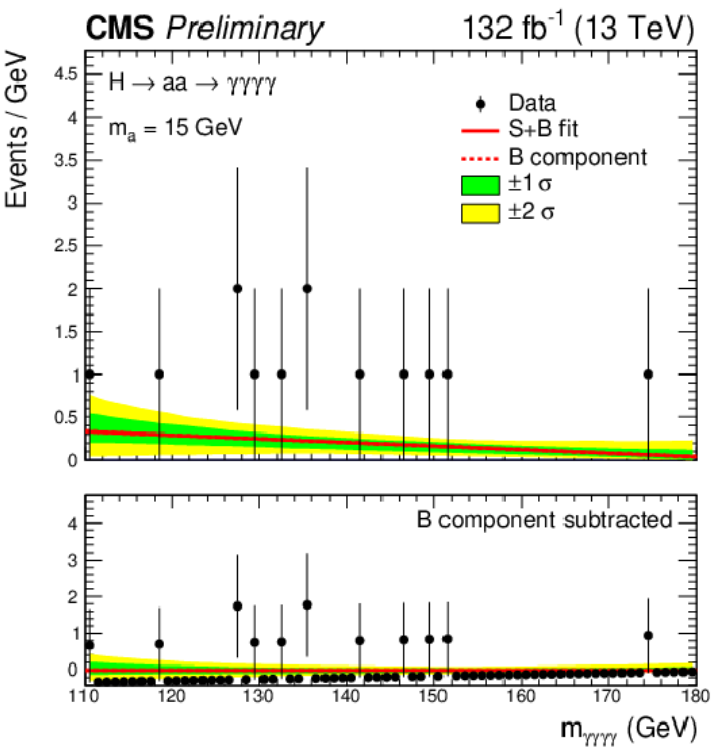


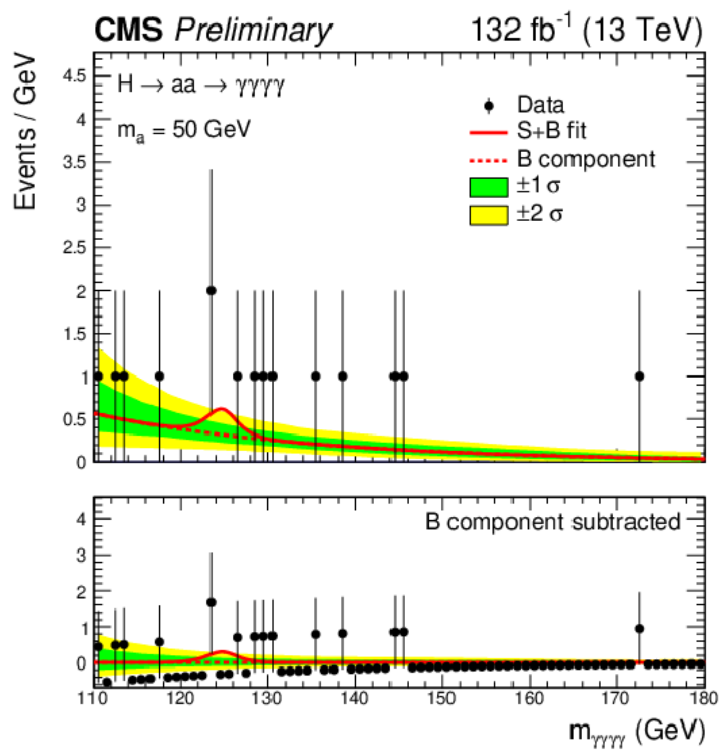
BDT training variables separate isolated photons originating from the decay of the pseudoscalar boson from those in the hard scatter or from non-prompt processes:

1. Photon identification (ID) variables for all four photons
2. The p_T of the two pseudoscalar candidates
3. The difference between the reconstructed invariant mass of the pseudoscalar candidates
4. The difference between invariant mass of the pseudoscalar candidate and the m_a(hyp) parameter divided by $m_{4\gamma}$
5. The angular distance $\Delta R(a_1,a_2)$ divided by $m_{4\gamma}$
6. The helicity angle ($\cos\theta_{a\gamma}$) between the leading pseudoscalar and the leading photon produced from its decay

$H(125) \rightarrow aa \rightarrow 4\gamma$

- ❑ $m_{4\gamma}$ mass peak signal plus smooth background fitted to data
- ❑ The **signal** shape for the $m_{4\gamma}$ distribution, for each nominal signal hypothesis constructed from simulation - double-sided Crystal Ball function
- ❑ The **background** model is built to describe the shape of the $m_{4\gamma}$ distribution that results from processes other than the decay of the Higgs boson





$H(125) \to aa \to 4\gamma$

CMS PAS HIG-21-003

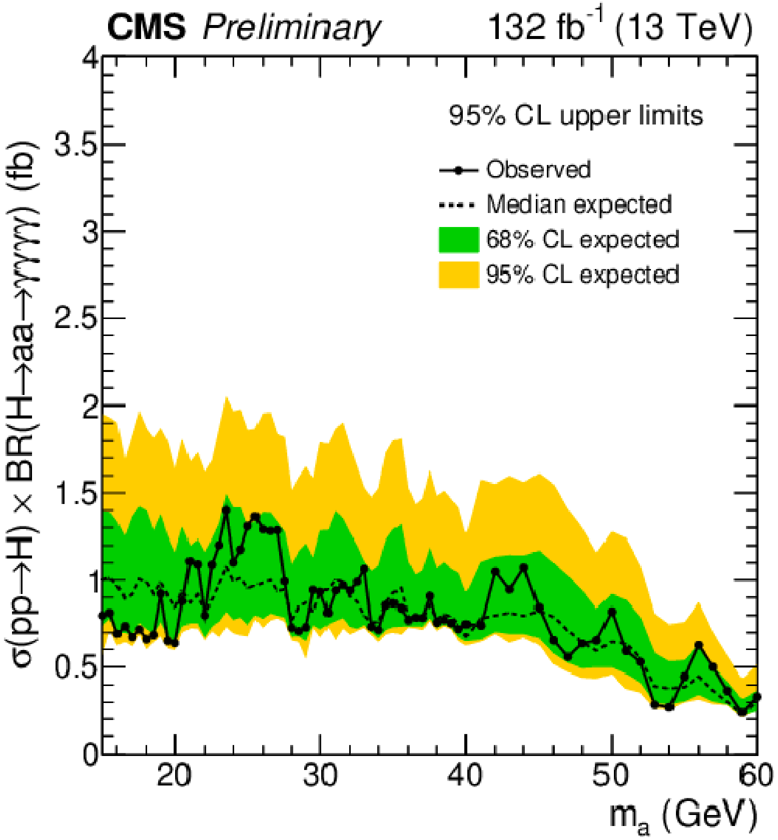
Unbinned maximum-likelihood fit performed to the $m_{4\gamma}$ distribution in the mass range $110 < m_{4\gamma} < 180$ GeV for each m_a hypothesis

No significant deviation from the **background-only hypothesis** observed.

Upper limits set at 95% CL on the product of the production cross section of the Higgs boson and the branching fraction into four photons via a pair of pseudoscalars

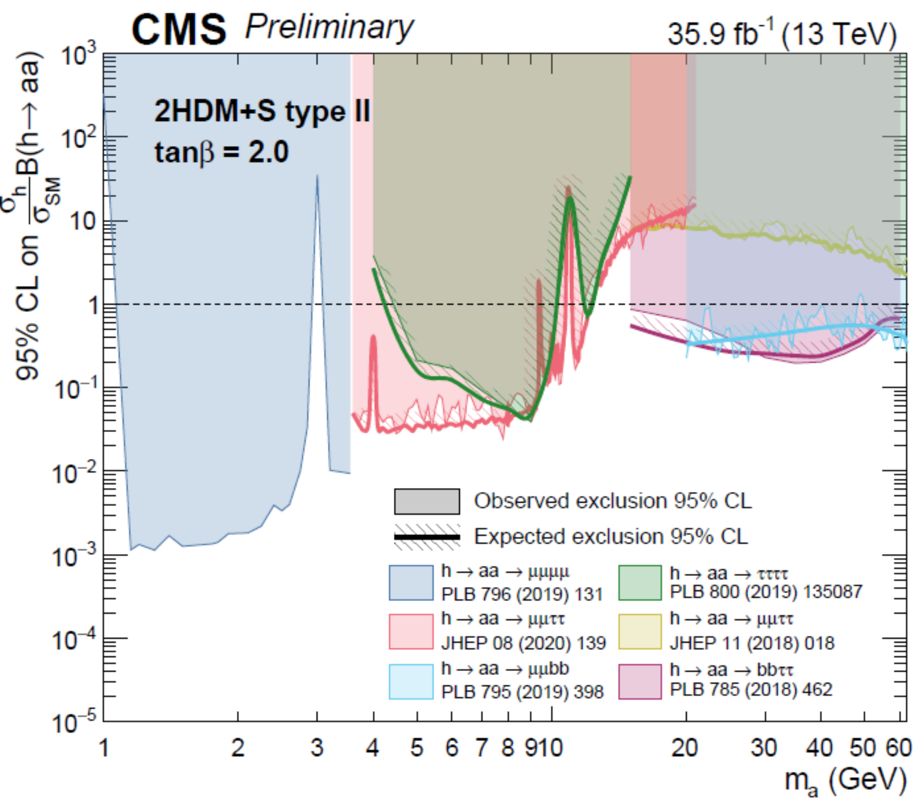
The observed (expected) limit ranges from

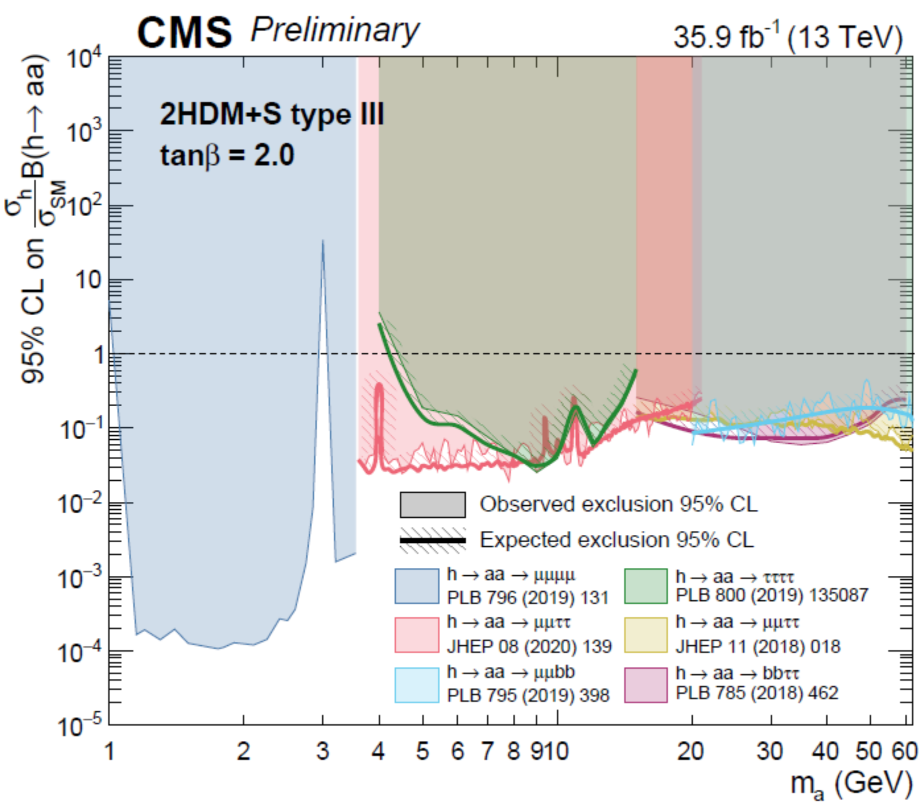
- ❑ 0.80 (1.00) fb for m_a = 15 GeV to
- ❑ 0.33 (0.30) fb for m_a = 60 GeV



H(125)→aa Summary

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





Branching fractions of the pseudoscalar boson to SM particles computed from the ref:
D. Curtin et al., "Exotic decays of the 125 GeV Higgs boson", PRD 90 (2014) 075004

Light Scalar $\rightarrow \gamma\gamma$

Light Scalar → γγ

$$M_{\gamma\gamma} = \sqrt{(4\, E_{\gamma_1} E_{\gamma_2}\, sin^2 \frac{\theta}{2})}$$

ECAL performance

Vertex Identification

- Clean final state signature: **2 isolated photons**

  Large smoothly-decreasing background (continuum)

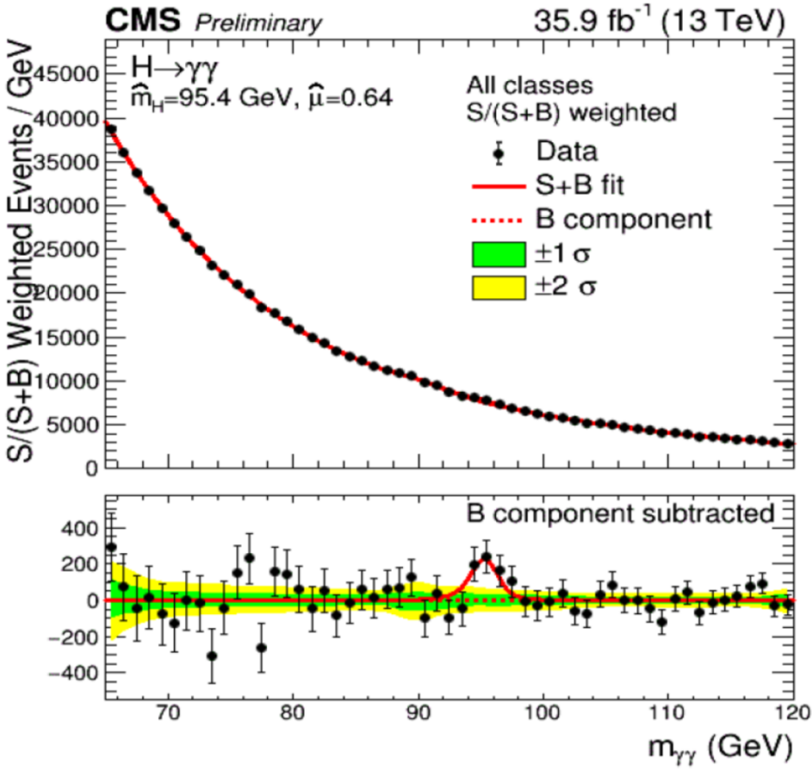
  1) **Reducible** (jet-jet and γ+jet with jet faking photon)

  2) **Irreducible** prompt diphoton production

- Low-mass analysis specificity: Drell-Yan background, with electrons from the Z boson misidentified as photons
  Use of a stricter electron veto based on the pixel detector
  Include relic DY contribution in background model

- Mass resolution is crucial (calibrations, energy regression and vertex identification)

- **Classification of γγ events** to gain in sensitivity
  Fits of S+B model over all event classes
  Each event weighted by the ratio S/(S+B) for its event class.



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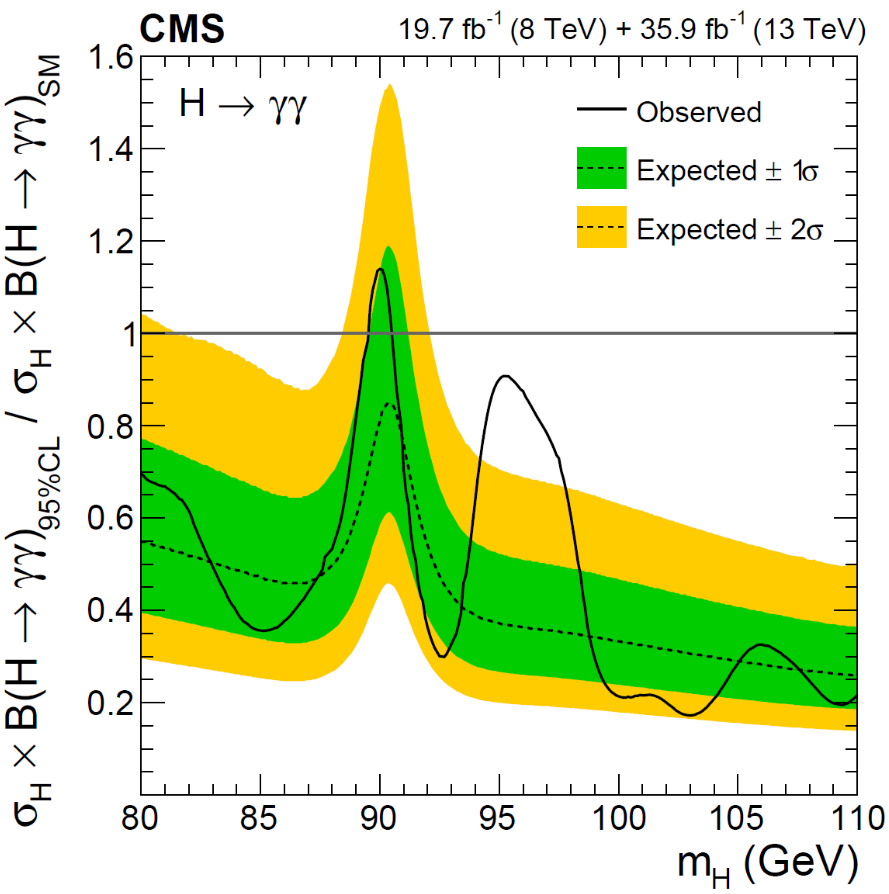

- 8 TeV+13 TeV: minimum (maximum) limit on (σ×Br)/ (σ×Br)SM: 0.17(1.15) at m=103.0 (90.0) GeV
- Combined 8 TeV+13 TeV: σ×BR limit normalized to SM expectation (production processes assumed in SM proportion)
- **There is an excess with respect to expected limits at m= 95.3 GeV**

13 TeV: Excess ~2.9 σ local (1.47σ global) significance at m=95.3 GeV

8TeV+13 TeV: Excess ~2.8σ local (**1.3σ global**) significance

More data are required to ascertain the origin of this mild excess

Summary & Outlook

✓Observed Higgs boson at mass 125 GeV may be part of an **extended Higgs sector**

✓ Many BSM models predicting new scalar and pseudoscalar neutral Higgs bosons (2HDM, MSSM, **NMSSM** …) have been explored at CMS

✓ **No signs of light Higgs bosons yet**; but now exploration with larger data sample at LHC Run-2, other searches targeting the very low mass region is ongoing (results expected soon)

✓ Exciting times ahead of us with ongoing full LHC Run II analysis and upcoming Run III data