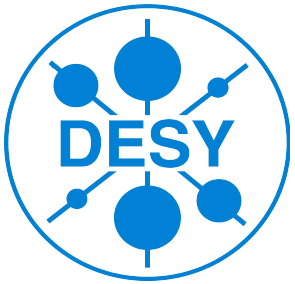

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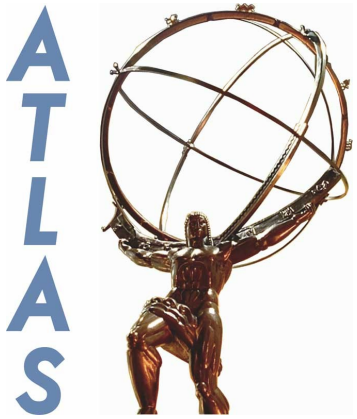


Searches for Exotic Higgs Bosons at ATLAS and CMS

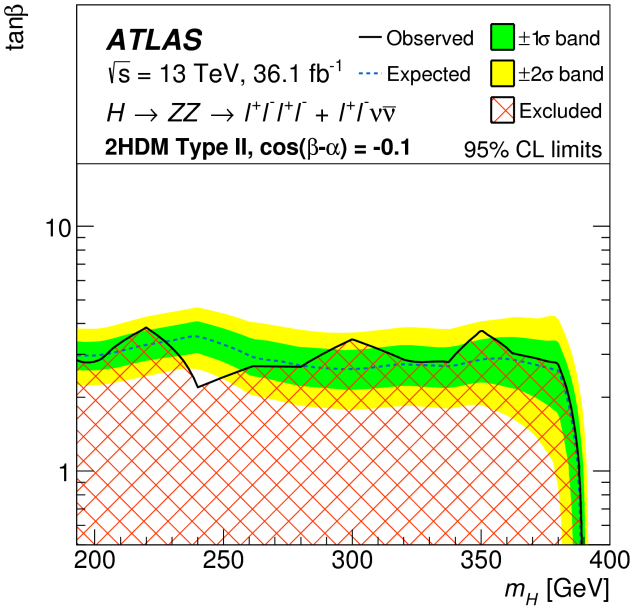
Alexei Raspereza

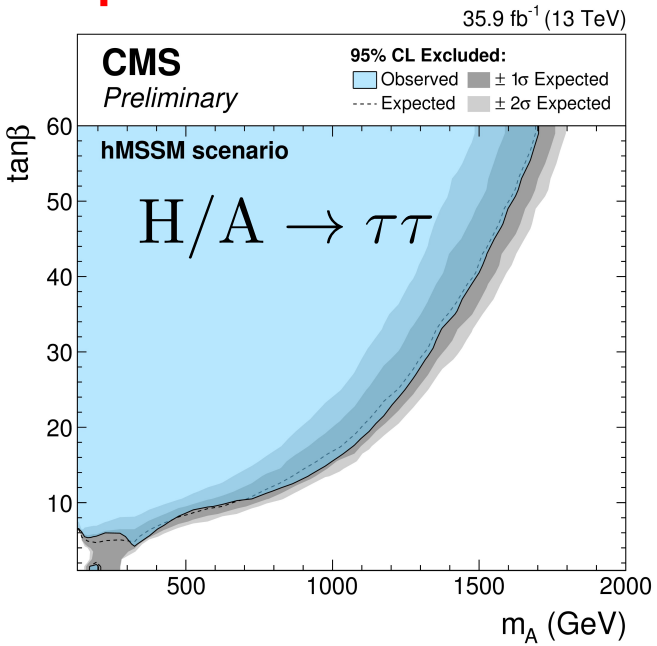
DESY – Hamburg

53rd Recontres de Moriond – QCD and High Energy Interactions, 17 – 24 March 2018

Introduction

- **Recent Higgs studies confirm that Electroweak Symmetry Breaking is realized via Brout-Englert-Higgs mechanism**
- **What is the structure of the Higgs potential? Two ways to address this question**
  - **high precision measurement of the discovered Higgs boson**
  - **search for additional Higgs bosons predicted by theories beyond SM (BSM)**
- **Main focus of BSM Higgs searches at LHC : general two Higgs doublet models (2HDM) and minimal supersymmetric standard model (MSSM)**
  - **no signal found yet → limits on model parameters are set**





- **This talk → searches for exotic Higgs bosons beyond 2HDM and MSSM**

2 Higgs Doublets + 1 Singlet Models

- **7 physical Higgs states : 2 CP-odd $a_{1,2}$, 3 CP-even $h_{1,2,3}$, 2 charged $h^{\pm}$**

- **example : next-to-MSSM**

  Higgs sector : 2HD+1S type-2

  solves μ-problem of MSSM

  $\lambda \hat{S} \hat{H}_u \hat{H}_d \rightarrow \mu_{\text{eff}} = \lambda \langle S \rangle$

	Type-1	Type-2	Type-3 (lepton-specific)	Type-4 (flipped)
Up-type quarks	Φ_2	Φ_2	Φ_2	Φ_2
Down-type quarks	Φ_2	Φ_1	Φ_2	Φ_1
Charged leptons	Φ_2	Φ_1	Φ_1	Φ_2
a_1 couplings to fermions				
Up-type quarks	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
Down-type quarks	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
Charged leptons	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

$$\tan\beta = v_{\Phi_2}/v_{\Phi_1}$$

- **Particular scenario**

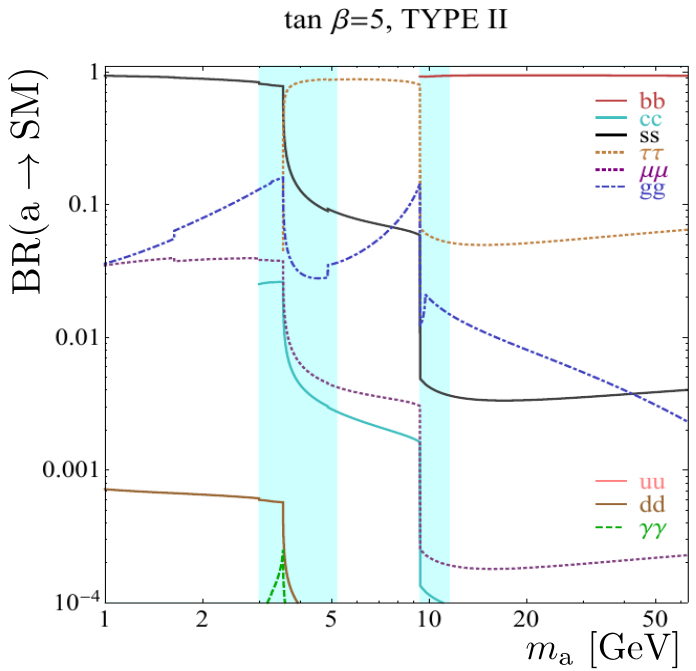
a_1 is very light ($2m_{a1} < m_{H(125)}$) and has large singlet component

→ **reduced couplings to fermions**

- **hard to detect via conventional production mechanisms**

  $gg \rightarrow a_1$ & bba_1

- **accessible via $H(125) \rightarrow a_1 a_1 \rightarrow (f_1\bar{f}_1)(f_2\bar{f}_2)$**



CMS H(125) → aa → (ττ)(bb) Search at 13 TeV

HIG-17-024

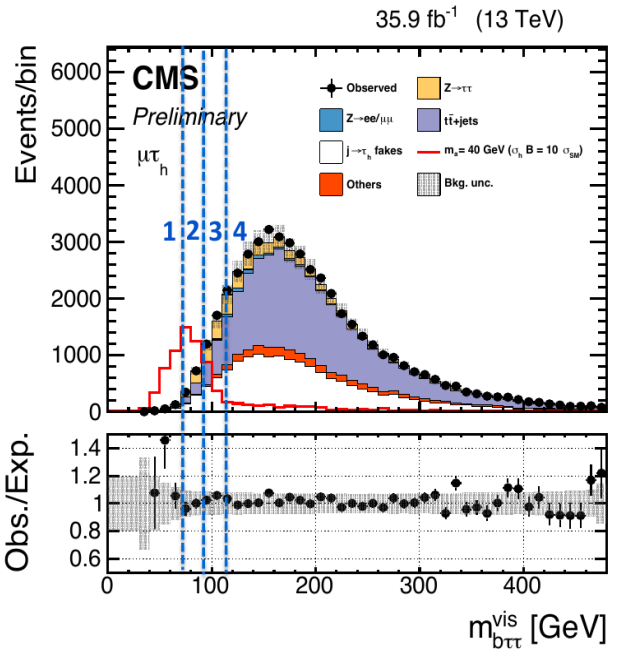
- **analyzed di-tau signatures :** $\tau_e\tau_\mu$, $\tau_e\tau_h$, $\tau_\mu\tau_h$
- **at least one b-tagged jet : p_T > 15 GeV, |η|<2.4**

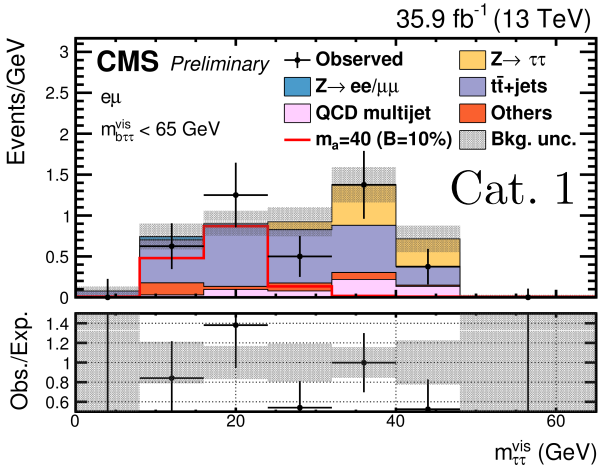
  in large fraction of signal events second b-jet is too soft
- **event categorization based on mass of selected τ candidates and b-jet**

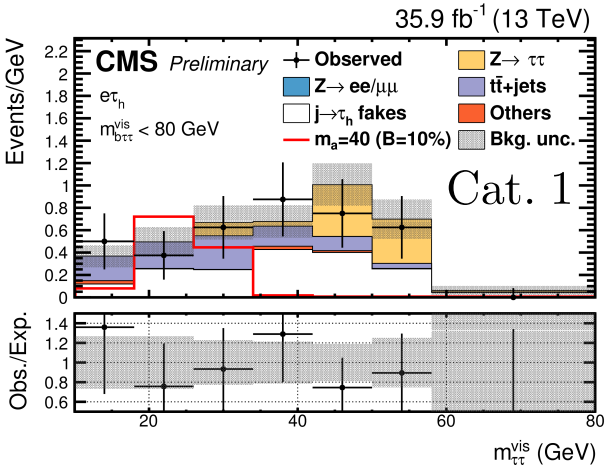
  low $m^{vis}_{b\tau\tau}$ categories have little background

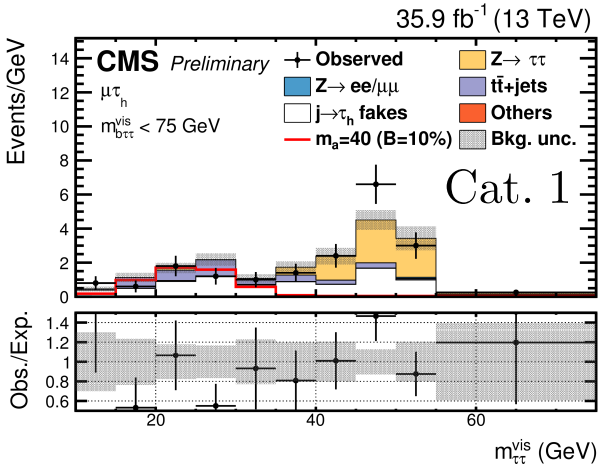
  → enhanced sensitivity

  highest $m^{vis}_{b\tau\tau}$ category : background control regions
- **signal is extracted from simultaneous fit to $m^{vis}_{\tau\tau}$ in all channels and all event categories**

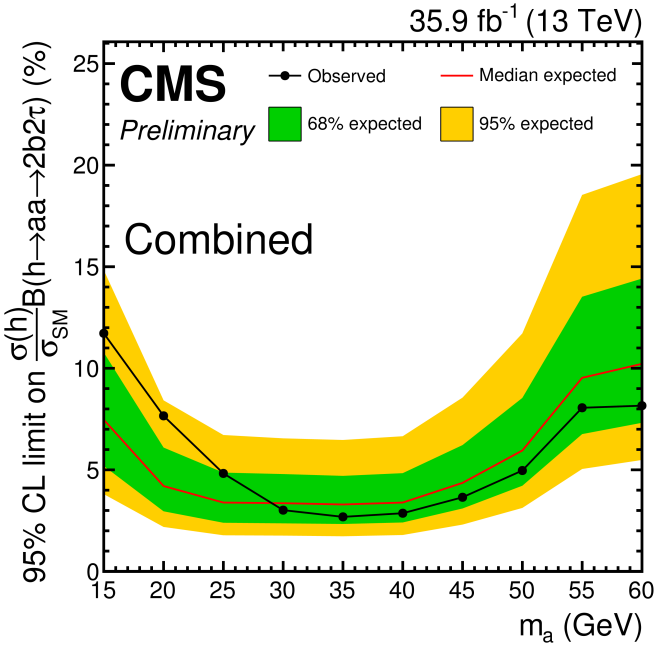


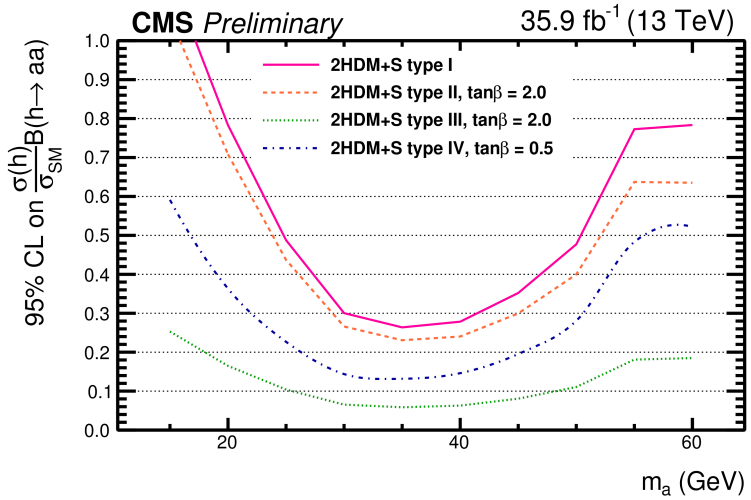




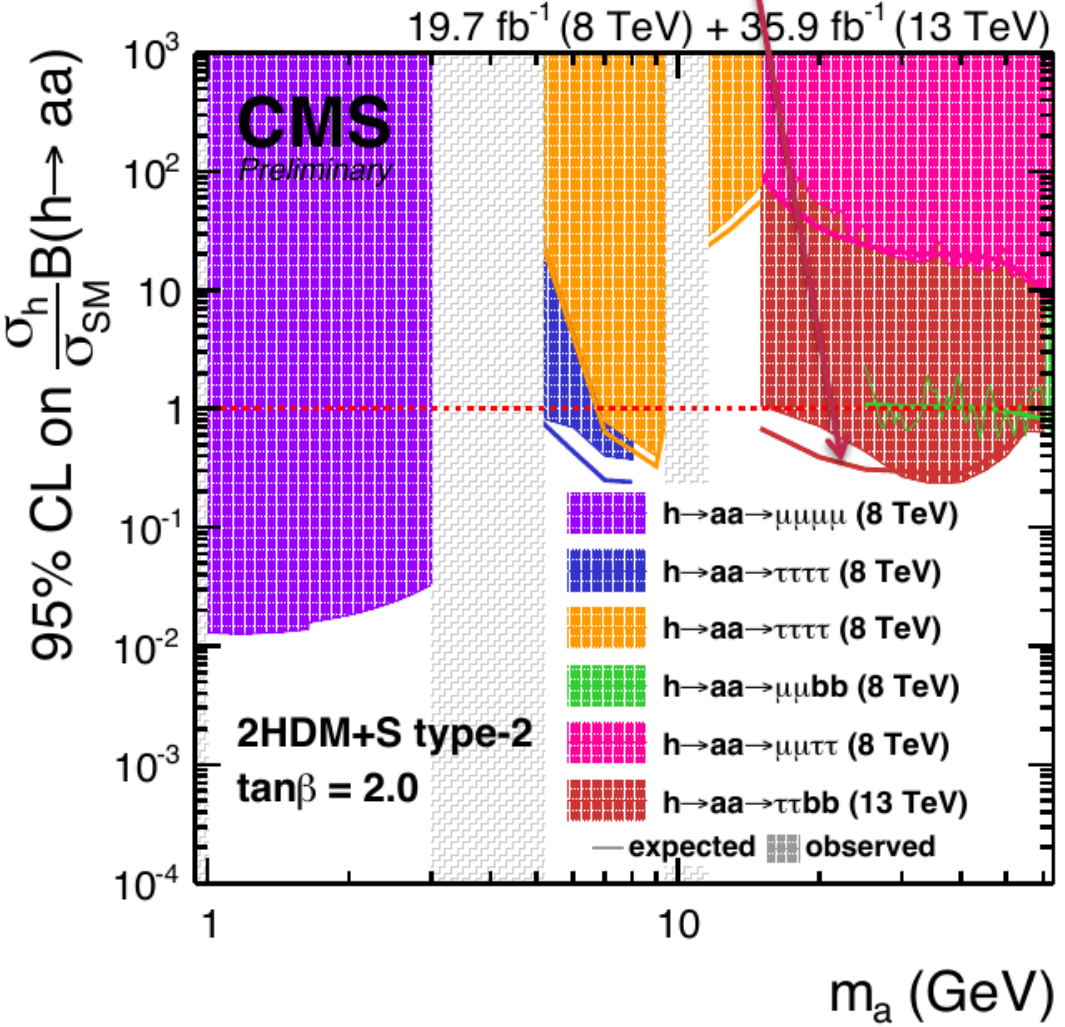


Interpretations of H(125) → aa → (ττ)(bb) Search





This result



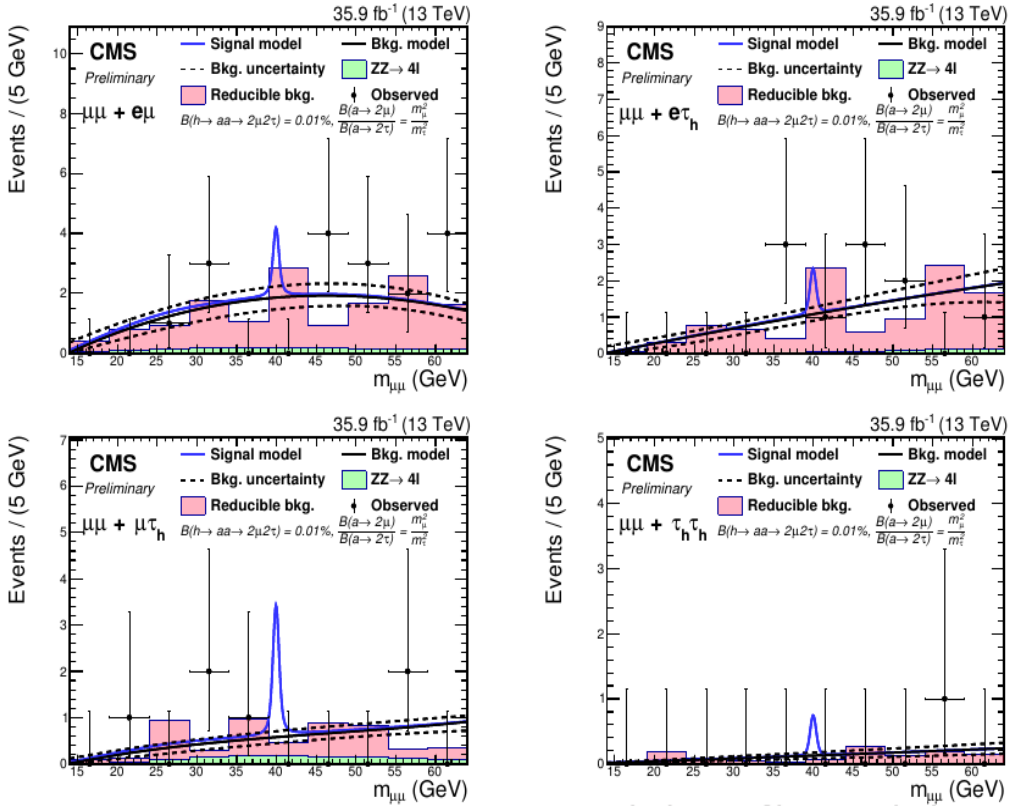
H(125) → aa → (μμ)(ττ) Search with CMS at 13 TeV

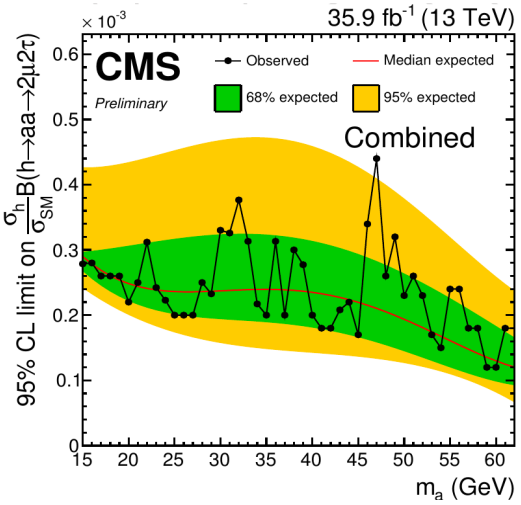
- **analyzed final states :** $\mu\mu + \tau_e\tau_\mu,\ \mu\mu + \tau_e\tau_h,\ \mu\mu + \tau_\mu\tau_h,\ \mu\mu + \tau_h\tau_h$ **HIG-17-029**
- **probed m_a range : 15 – 62.5 GeV**

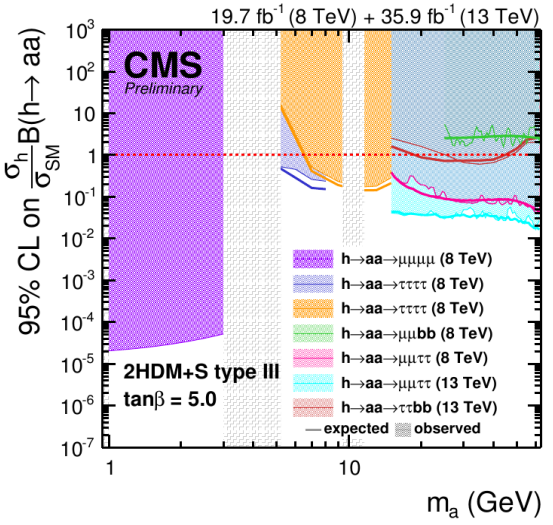
$m_a \geq$ 15 GeV : sizable angular separation between leptons in a → μμ (ττ) decays

→ selection of isolated leptons

- **signal extracted from fit to $m_{\mu\mu}$ of a → μμ candidate**







No significant access in any channel

ATLAS H(125) → aa → 4μ Search at 13 TeV

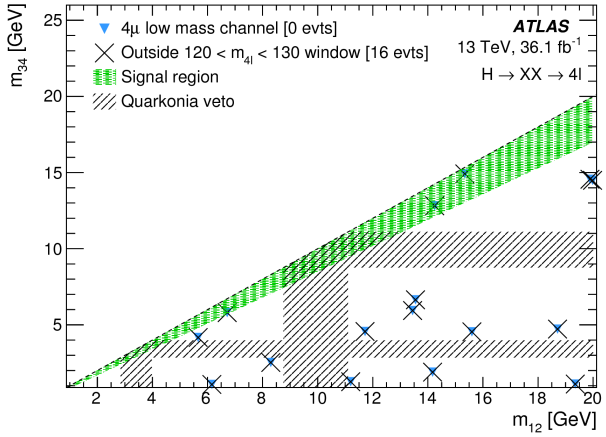
- **selection of** $(\mu^+\mu^-)(\mu^+\mu^-)$ **events :**

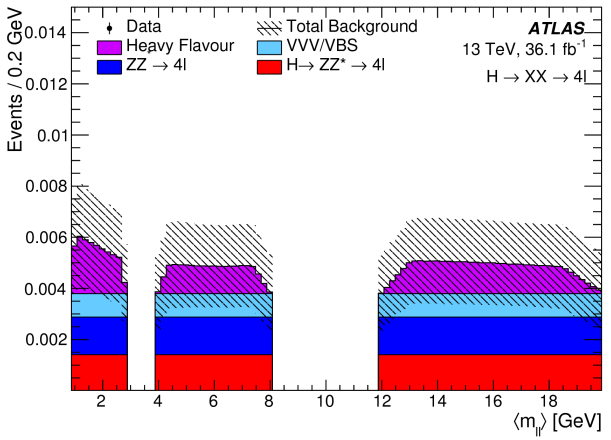
arXiv:1802.03388

$$0.88 < m_{12,34} < 20 \text{ GeV}, \quad 120 < m_{4\mu} < 130 \text{ GeV}$$

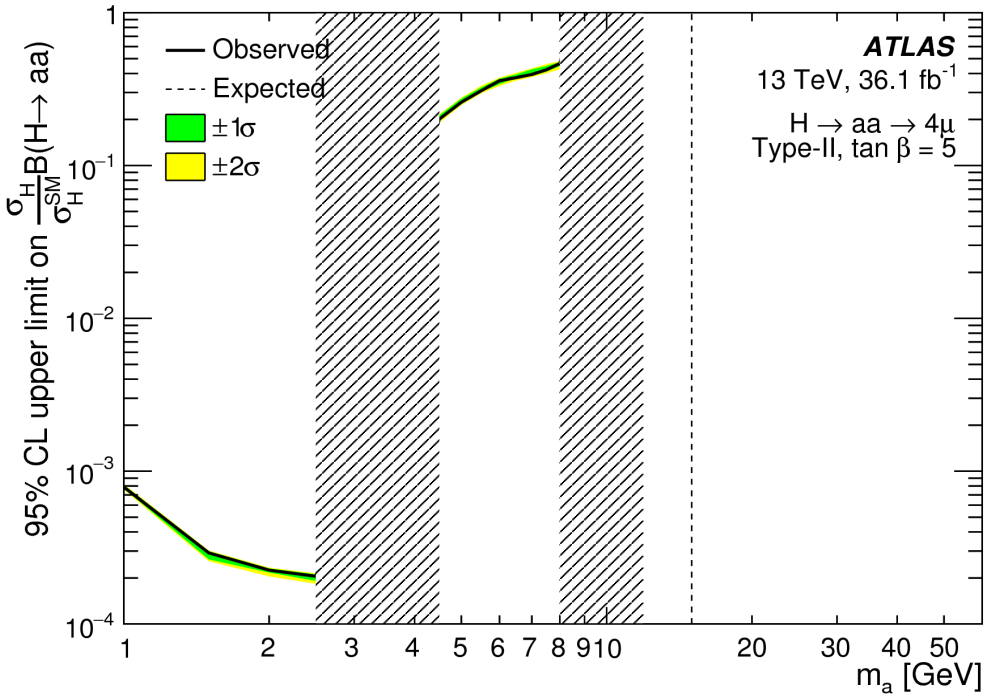
$$m_{34}/m_{12} > 0.85$$

$m_{12,34}$ **– invariant masses of** $\mu^+\mu^-$ **pairs,** $m_{12} > m_{34}$





probed m_a range : 1 – 15 GeV



Phenomenology of Models with $H^{\pm\pm}$

- ***H*±± appear in Higgs triplet models attempting to explain neutrino mass hierarchy**
  - **type-II see-saw models**
  - **left-right symmetric (LRS) models**

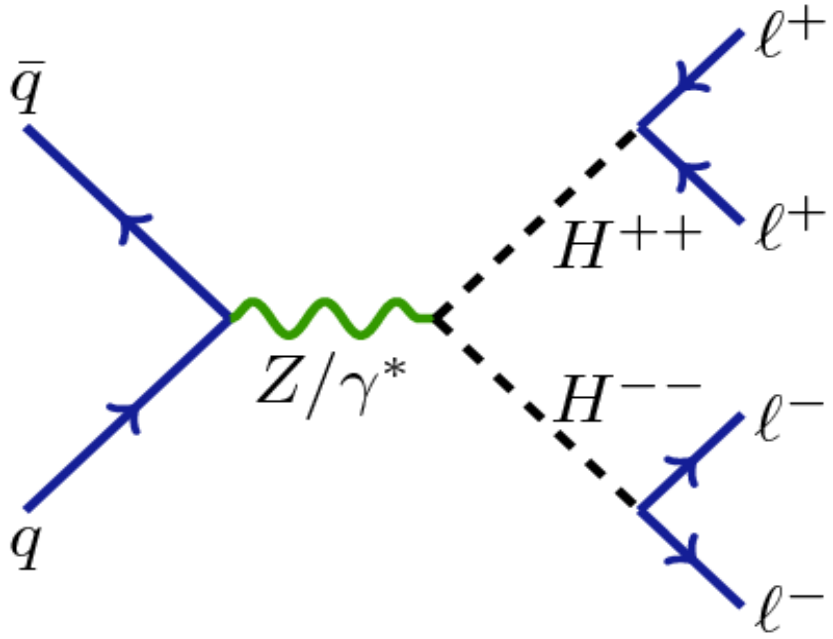
    distinguish between $H_L^{\pm\pm}$ and $H_R^{\pm\pm}$ (couple to ℓ_L and ℓ_R, respectively)

    $H_L^{\pm\pm}$ and $H_R^{\pm\pm}$ have different couplings to Z boson

- **experimental signatures**

$$q\bar{q} \to Z/\gamma^* \to H^{++}H^{--}$$

$$H^{\pm\pm} \to W^{\pm}W^{\pm} \quad \text{or} \quad H^{\pm\pm} \to \ell_i^{\pm}\ell_j^{\pm}$$



- **for many models mass-coupling relation doesn't hold for *H*±±**

  → no preference for decays to $\tau^{\pm}\tau^{\pm}$

  → high sensitivity is provided by decays into lighter leptons

$$H^{\pm\pm} \to e^{\pm}e^{\pm},\ \mu^{\pm}\mu^{\pm},\ e^{\pm}\mu^{\pm}$$

ATLAS Search for $H^{\pm\pm}$ at 13 TeV

- **Analysis searches for $H^{\pm\pm}$ in multi-lepton final states from $H^{++}H^{--}$ production**

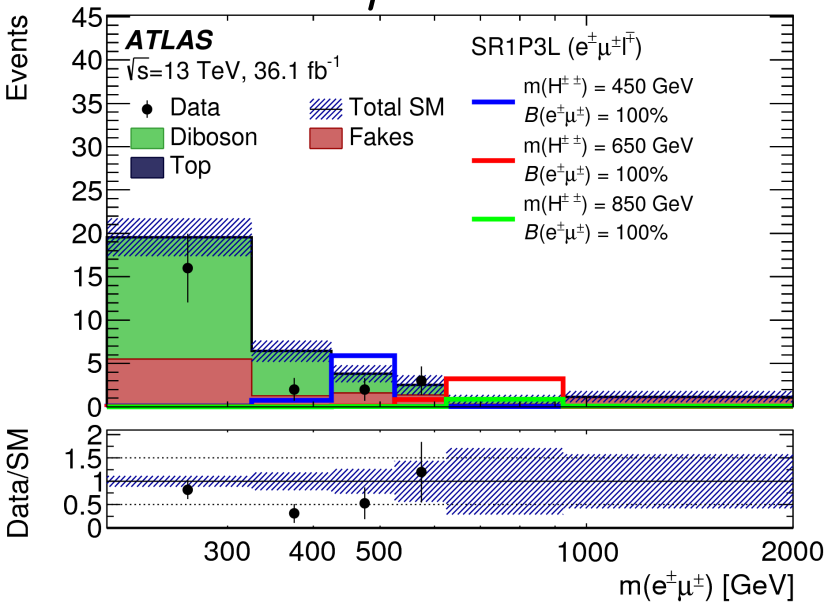
arXiv:1710.09748

- **Events classified in various categories based on**
  - **lepton multiplicity and lepton flavor composition**
- **Signal is extracted from simultaneous fit to mass variables in all categories**

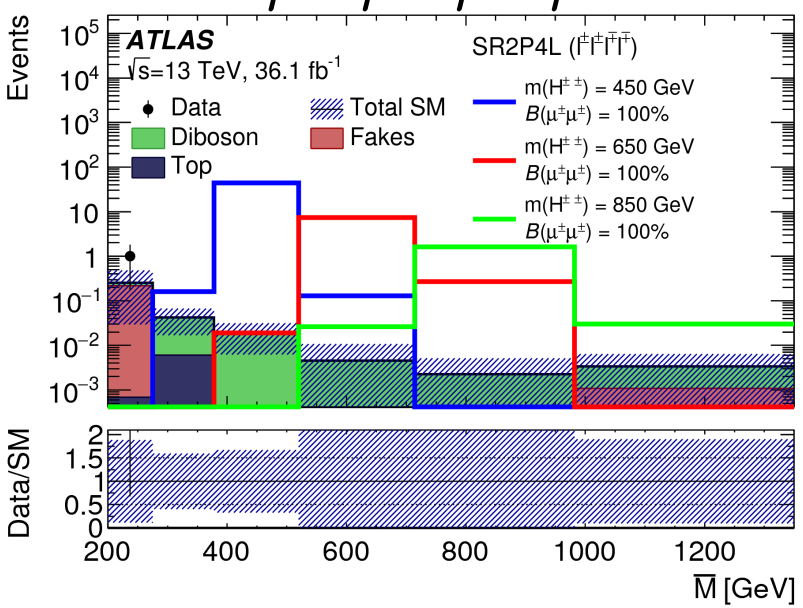
2-lepton and 3-lepton regions : mass of the same sign lepton pair

4-lepton region : average mass of two same-sign lepton pairs

$e^{\pm}\mu^{\pm}\ell^{\mp}$

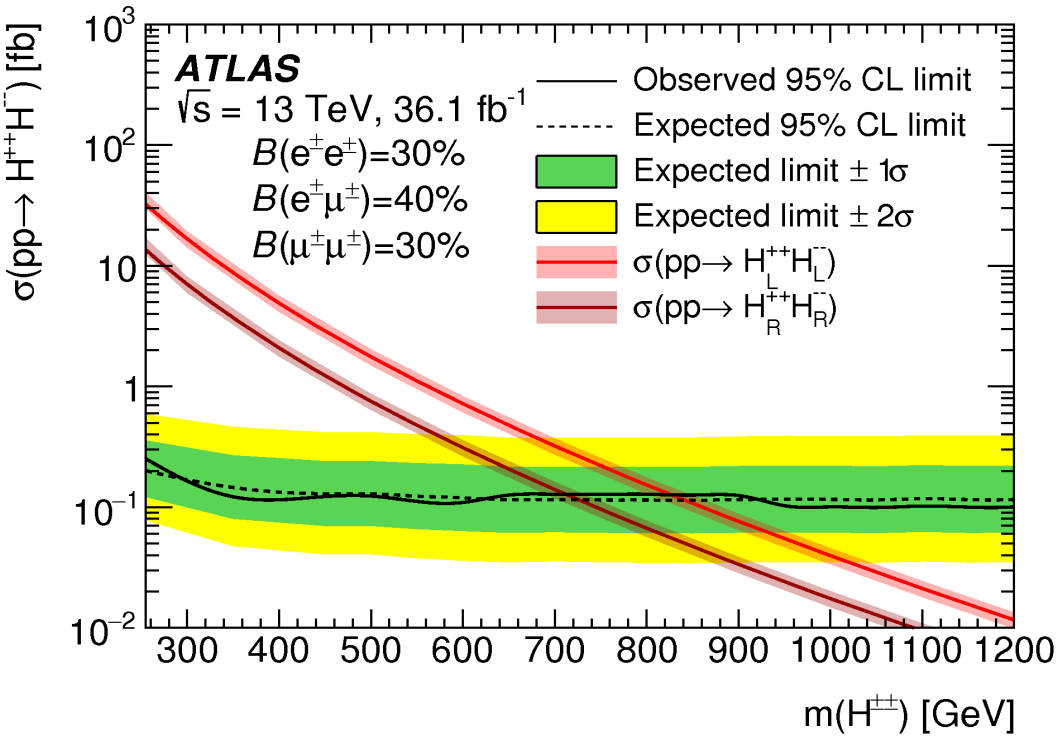


$\mu^{+}\mu^{+}\mu^{-}\mu^{-}$



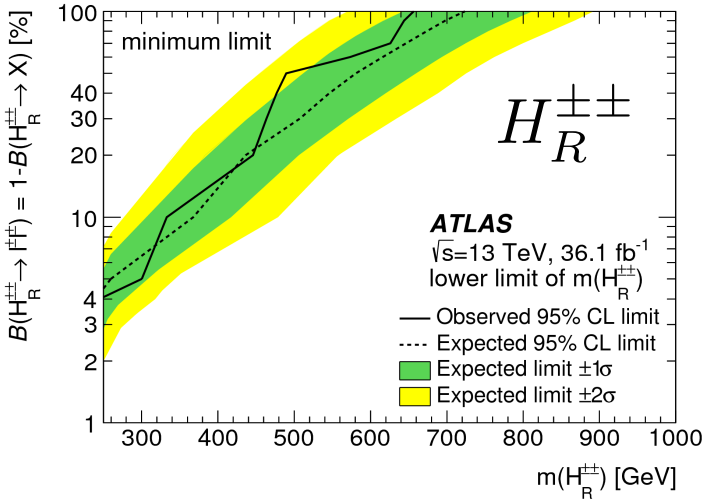
Interpretations of $H^{\pm\pm}$ Search

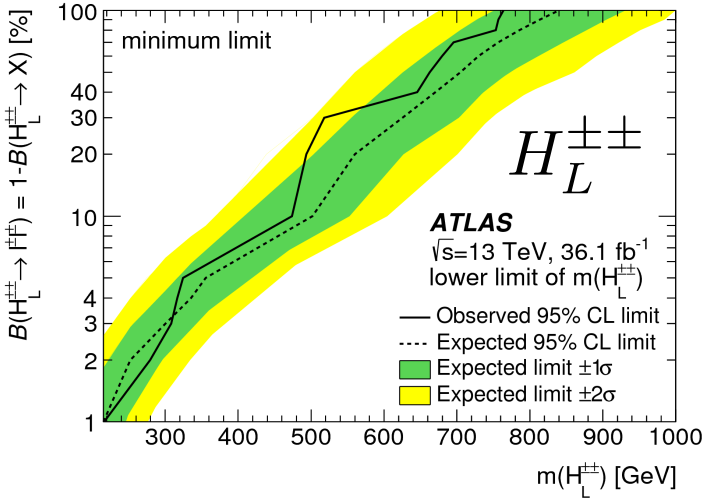
- **no signal is observed in $H^{\pm\pm}$ search**
- **limit on BR($H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$) and $\sigma(pp \to H^{++}H^{--})$ are set under various model assumptions**
- **few representative examples are given here**



least stringent limit on

$$B(H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}) \equiv \sum_{\ell_i,\ell_j=e,\mu} B(H^{\pm\pm} \to \ell_i^{\pm}\ell_j^{\pm})$$





Summary

- **Various searches are performed by ATLAS and CMS for exotic Higgs bosons beyond 2HDM and MSSM**
  - **generic 2HD+1S models**
  - **models with $H^{\pm\pm}$**
- **Searches reveal no signal so far**
- **Constrains are set on model parameters**
- **Collaborations are extending scope and enhancing sensitivity of these searches by**
  - **considering more experimental signatures**
  - **improving experimental techniques**

Backup

Summary of Run1 H(125) → aa Searches at CMS

- **most of CMS H(125) → aa searches at CMS are performed inclusively**

$$H(125) \to aa \to (\mu^+\mu^-)(\mu^+\mu^-)$$

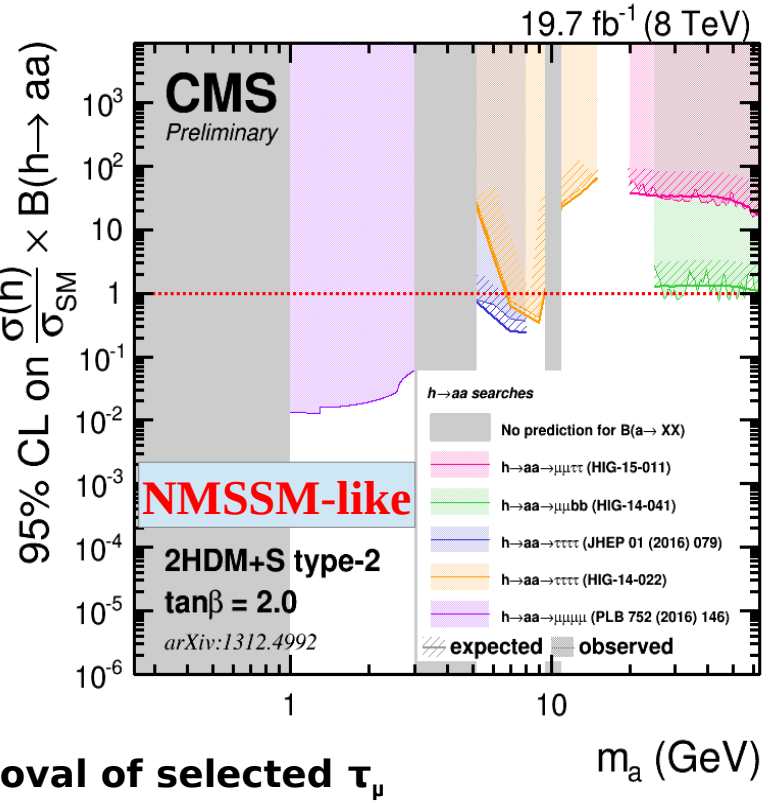
- **clean signature : two boosted $\mu^+\mu^-$ pairs**
- **low background : mainly QCD multijets with muons from quarkonia and b/c-hadron decays (estimated from data)**
- **signal : resonant peak in 2D mass distribution of boosted muon pairs**

$$H(125) \to a_1 a_1 \to (\tau_\mu^\pm \tau_{\text{1-prong}}^\mp)(\tau_\mu^\pm \tau_{\text{1-prong}}^\mp)$$

- **signature : two same sign muons each accompanied by single track**
- **major background : QCD multijet (measured in data)**
- **signal extracted from 2D mass distribution of muon-track pairs**

$$H(125) \to a_1 a_1 \to (\tau_\mu \tau_X)(\tau_\mu \tau_X)$$

- **sensitivity is enhanced by exploiting VH production mode in addition to gg → H**

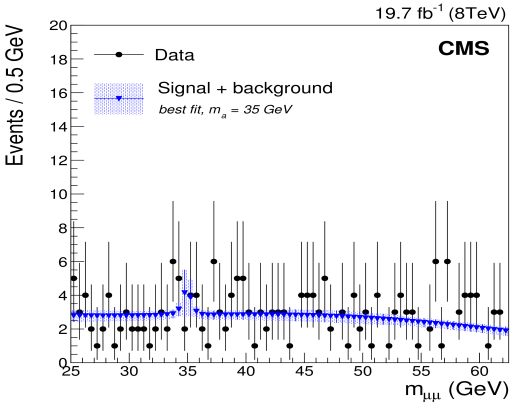


- **boosted τ pairs : τ_X identification after removal of selected τ_μ**
- **event categorization based on m_T of triggering muon and missing E_T**
- **counting experiment after mass cuts with $m_{\mu+x}$ > 4 GeV**

Summary of Run1 H(125) → aa Searches at CMS

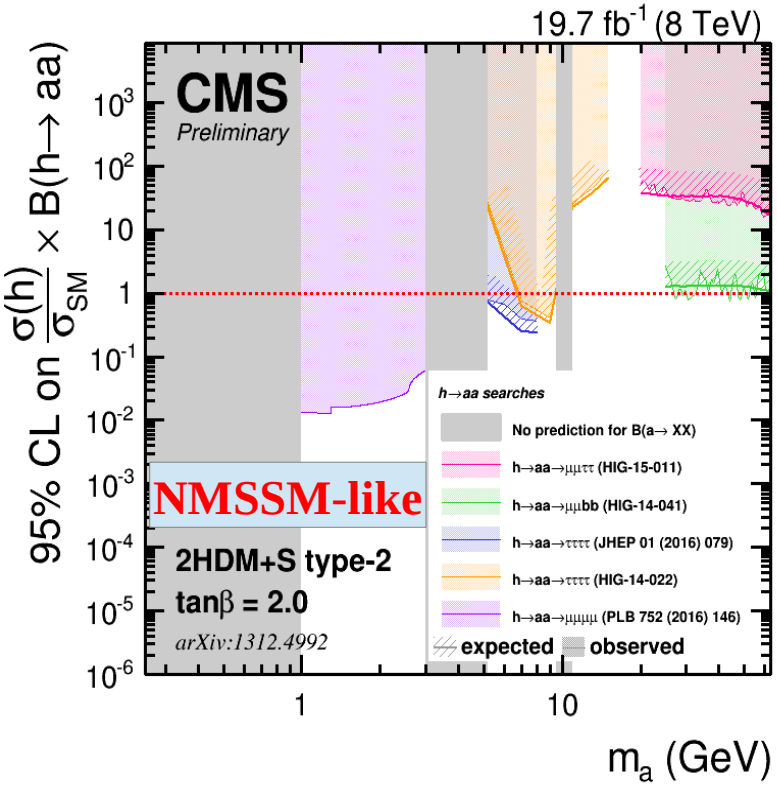
$H(125) \to aa \to (\mu^+\mu^-)(b\bar{b})$

- **cut on invariant mass of selected objects : $|m_{bb\mu\mu} - 125\ GeV| < 25\ GeV$**
- **largest backgrounds : low mass Drell-Yan and top-pair events**
- **signal extracted from analytical fit of $m_{\mu\mu}$ spectrum**



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

- **exploited di-tau signatures**
  $\tau_e\tau_e,\ \tau_e\tau_\mu,\ \tau_e\tau_h,\ \tau_\mu\tau_h,\ \tau_h\tau_h$
- **largest backgrounds : irreducible ZZ and WZ, WW and QCD with jet → τ fakes**
- **signal is extracted from analytical fit of $m_{\mu\mu}$ spectrum**



- **Both analyses are insensitive yet to NMSSM scenarios**

Summary of Run1 H(125) → aa Searches at CMS

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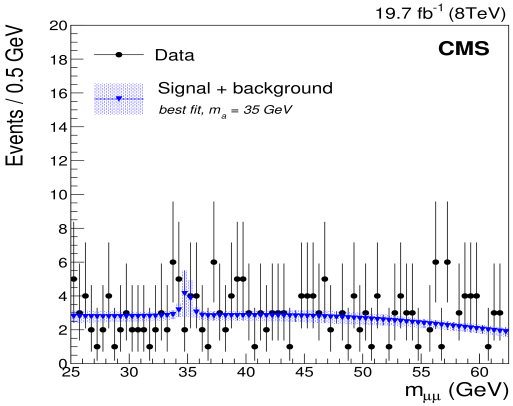
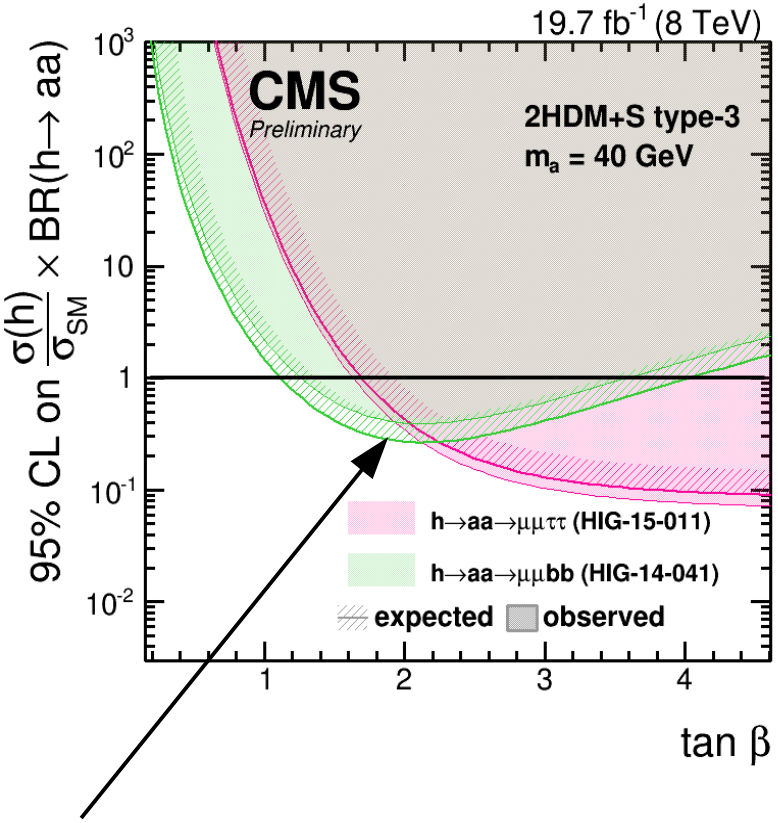


$H(125) \to aa \to (\mu\mu)(\tau\tau)$

- **Exploited di-tau signatures**
  $\tau_e\tau_e,\ \tau_e\tau_\mu,\ \tau_e\tau_h,\ \tau_\mu\tau_h,\ \tau_h\tau_h,$
- **Largest backgrounds : irreducible ZZ and WZ, WW and QCD with jet → τ fakes**
- **Signal is extracted from analytical fit of $m_{\mu\mu}$ spectrum**



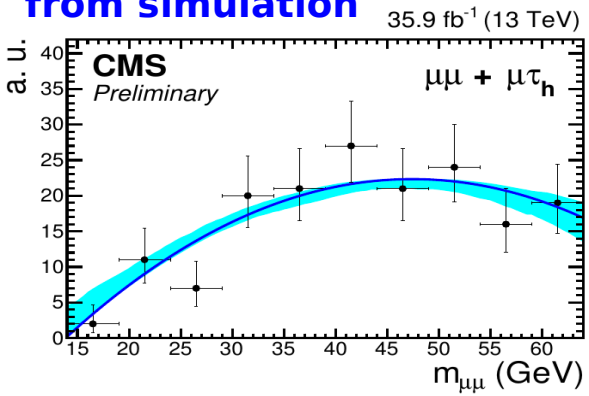
- **Both analyses are insensitive yet to NMSSM scenarios but provide constrains on alternative 2HD+1S models**

Signal extraction in H(125) → aa → (μμ)(ττ) Search

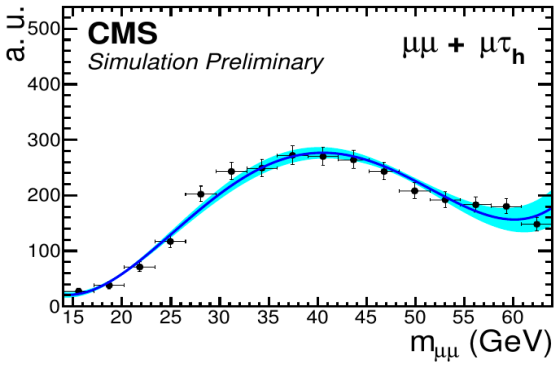
Signal extracted from fit to mass spectrum of reconstructed a → μμ candidate

background shape modeling : Bernstein polynomials

irreducile (ZZ) estimated from simulation



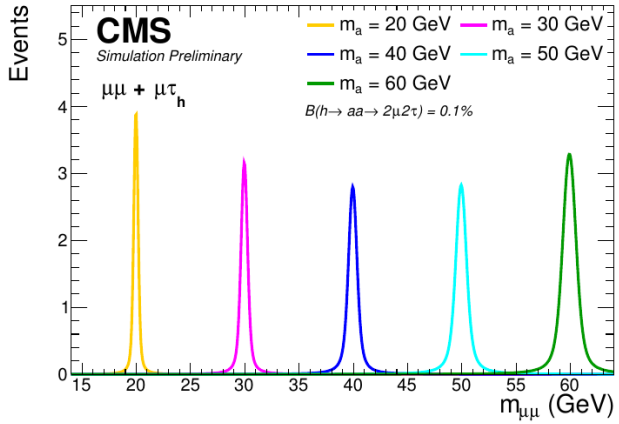
reducible (ZZ → 2ℓ+2q, ttbar, QCD) : from sideband with SS, loosely isolated τ candidates



signal shape modeling

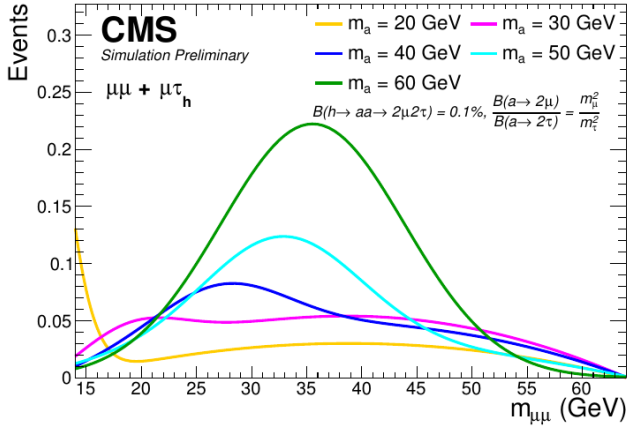
H(125) → aa → (μμ)(ττ) component

Voigtian = Gaussian ⊗ Lorentz profile



H(125) → aa → ($\tau_\mu\tau_\mu$)(ττ) component

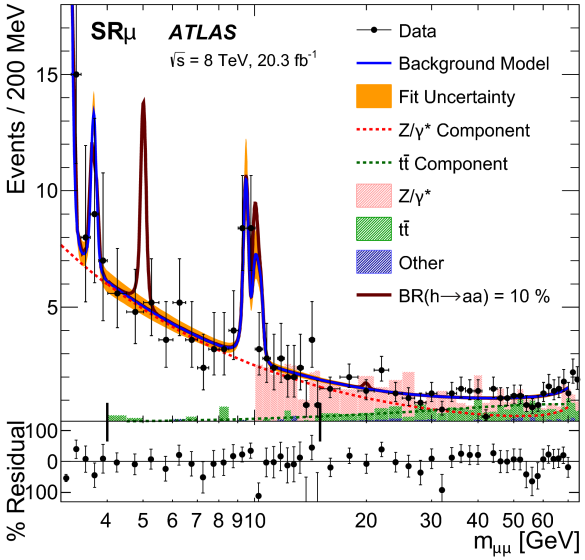
Gaussian + polynomial

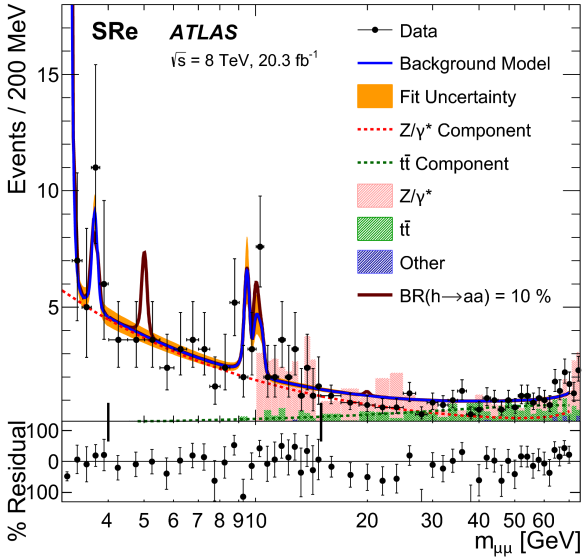


H(125) → aa → (μμ)(ττ) Search with ATLAS at 8 TeV

Phys. Rev. D92 (2015) 052002

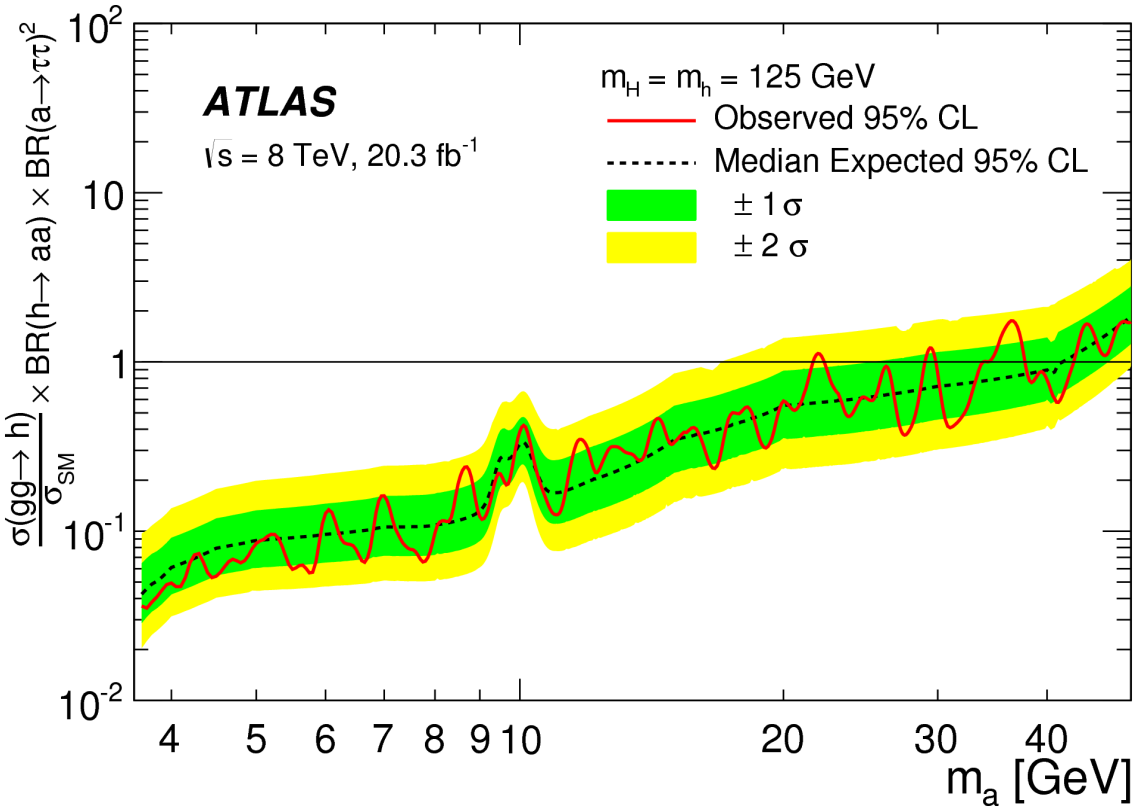
- search extends in m_a down to a → ττ decay threshold (m_a ~ 3.75 GeV)
  - $\mu^+\mu^-$ pairs with invariant mass in the range 2.8 – 70 GeV are selected
  - one τ is identified via leptonic decay $\tau \to \ell\nu_\ell\nu_\tau,\ \ell = \mathrm{e}, \mu\ (\tau_\ell)$
  - for low m_a a boson is Lorentz boosted & its decay products are collimated → τ_ℓ candidate is accompanied by 1, 2 or 3 nearby tracks with leading track having opposite sign w.r.t. τ_ℓ candidate
- two signal regions are defined by flavor of lepton from tau decay : SRμ & SRe
- signal is extracted from simultaneous fit of $m_{\mu\mu}$ spectrum of a → μμ candidate in two signal regions





ATLAS H(125) → aa → (μμ)(ττ) Search Results

- **Results of the search are used to set limit on**

$$\frac{\sigma(\mathrm{gg} \to \mathrm{h})}{\sigma_{\mathrm{SM}}} \times \mathrm{BR}(\mathrm{h} \to \mathrm{aa}) \times \mathrm{BR}^2(\mathrm{a} \to \tau\tau)$$

under assumption $\dfrac{\Gamma(\mathrm{a} \to \mu\mu)}{\Gamma(\mathrm{a} \to \tau\tau)} = \dfrac{m_\mu^2}{m_\tau^2 \sqrt{1 - \left(2m_\tau / m_{\mathrm{a}}\right)^2}}.$