Searches for BSM Higgs bosons at CMS

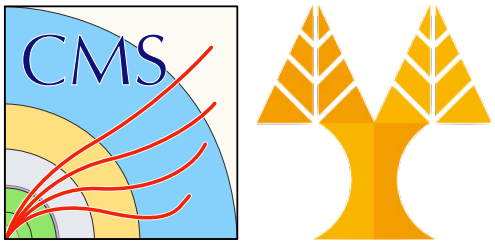
TeVPA2021: TeV Particle Astrophysics 2021 (24-29 Oct 2021)

S. Konstantinou[1]

on behalf of the CMS Collaboration

[1]University of Cyprus

26 Oct 2021



Introduction

Many beyond the standard model (BSM) theories predict the extension of the Higgs sector

- Minimal possible extensions are the two-Higgs-doublet models (2HDMs) — MSSM
  - Introduce an adddional Higgs doublet
  - Predict 5 Higgs bosons: CP-even h^0, H^0, CP-odd A, $H^{\pm}$
- 2HDM extensions add one singlet field (2HDM+S) — NMSSM
  - Two additional Higgs bosons $h^{'}$ and $A^{'}$
- Higgs triplet models introduce a scalar triplet — GEORGI-MACHACEK
  - Predict the presence of $H^{\pm\pm}$

The observation of an additional Higgs particle would be an evidence of new physics!

Introduction

CMS is broadening the searches of extended Higgs sectors

- New signal signatures, extended phase space, modern techniques, ...
- This talk presents the latest CMS results
  - Exotic decays of SM H(125) are not covered

2016 data (35.9 fb^{-1})

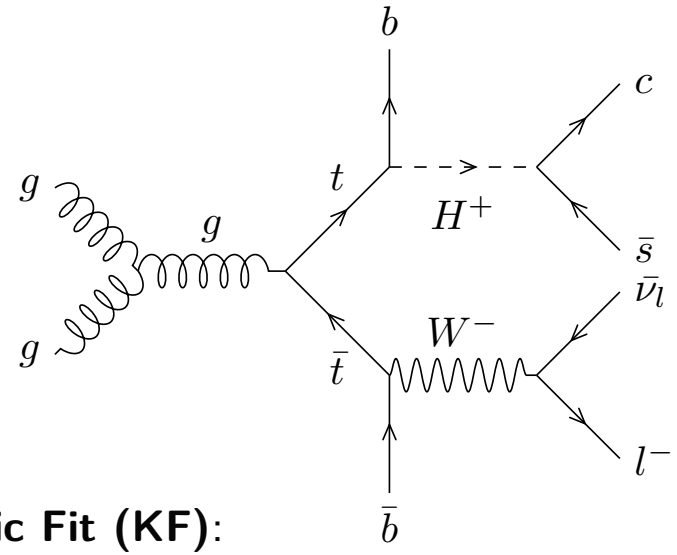
- $\mathrm{H}^{\pm} \to \mathrm{cs}$
- $\mathrm{H} \to \alpha\alpha \to \mu\mu\tau\tau$

Full Run II data (137 fb^{-1})

- $\mathrm{H}^{\pm(\pm)} \to \mathrm{W}^{\pm}\mathrm{Z}_0(\mathrm{W}^{\pm}\mathrm{W}^{\pm})$
- $\mathrm{H} \to \mathrm{h}(125)\mathrm{h}_\mathrm{S} \to \tau\tau\mathrm{bb}$
- $\mathrm{H}_1\mathrm{H}_1 \to$ bbbb (SUSY cascade decays)

Searches with 2016 data

- Light $H^{\pm}$ with $m_{H^{\pm}} < m_t$
- $\mathcal{B}(H^{\pm} \to cs)$ dominant for low $\tan\beta$ in 2HDM Type II
- ℓ+jets (e or μ) FS characterized by:
  1 isolated ℓ, $\geq$ 4 jets ($\geq$2 b jets, $\geq$ 1 c jet), p_T^{miss}
- Main background: $t\bar{t}$, Single-t, QCD, V+jets, Diboson

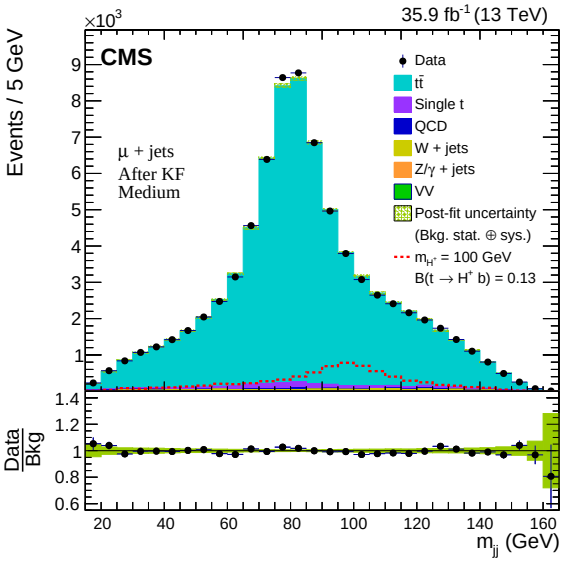


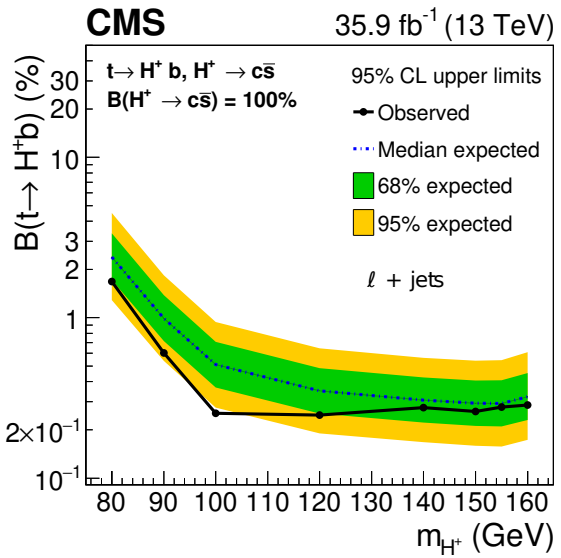
QCD bkg estimated from data ("ABCD"):

- Shapes: high p_T^{miss}, anti-isolated ℓ region
- Normal.: low p_T^{miss}, (anti-)isolated ℓ regions

Kinematic Fit (KF):

- Corrects 4-vectors of physical objects
- Constraints on $m^{inv}_{b_{had}q\bar{q}} = m^{inv}_{b_{lep}\ell\nu_\ell} = m_t$



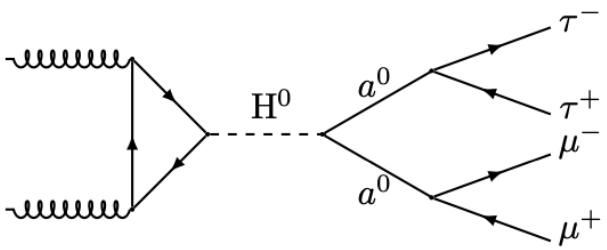


- Categorization based on c-tagging WP (L,M,T)
- Fit on m_{jj} of non-b jets
- Upper limits of 1.68-0.25 for $m_{H^{\pm}}$ = 80-160 GeV
- No signal excess above the SM background prediction

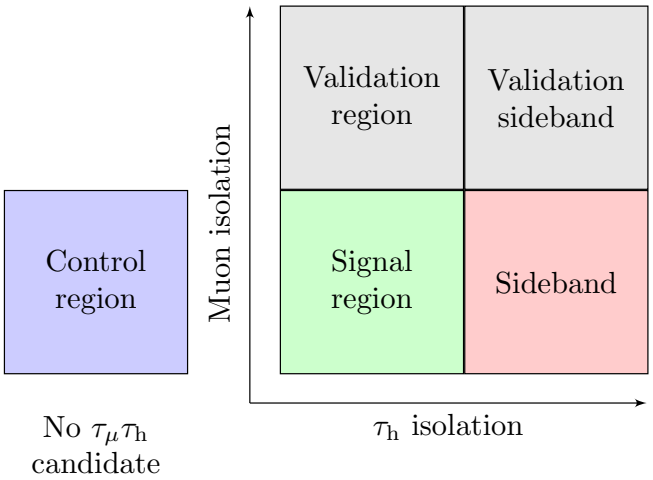
SM-like H production via ggF or VBS decaying into a pair of light pseudoscalars α

- Focus on $m_H \geq 125$ GeV and $3.6 \leq m_\alpha < 21$ GeV
  - High Lorentz boost because of $m_H \gg m_\alpha$
- Final state contains: $2\mu^{OS}$ & boosted $\tau_\mu\tau_h$
- τ-pair reconstruction technique targets boosted $\tau_\mu\tau_h$

gluon gluon fusion



Data modeling: Fit 2D $m_{\mu\mu} \times m_{\mu\mu\tau_\mu\tau_h}$ (in 3 $m_{\mu\mu}$ bins)



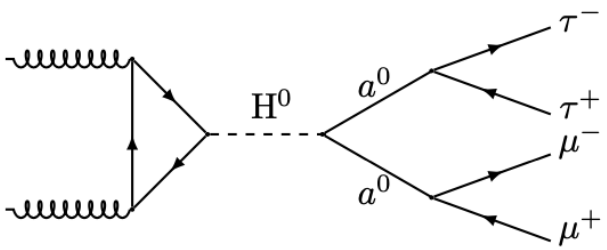
- Bkg in SR from sideband & normalized with "tight-to-loose" ratio
- "tight-to-loose" ratio verified in validation regions
- Relative ratio of the resonances are fixed from the CR

$H \to \alpha\alpha \to \mu\mu\tau\tau$ arXiv:2005.08694

SM-like H production via ggF or VBS decaying into a pair of light pseudoscalars α

- Focus on $m_H \geq 125$ GeV and $3.6 \leq m_\alpha < 21$ GeV
  - High Lorentz boost because of $m_H \gg m_\alpha$
- Final state contains: $2\mu^{OS}$ & boosted $\tau_\mu\tau_h$
- τ-pair reconstruction technique targets boosted $\tau_\mu\tau_h$

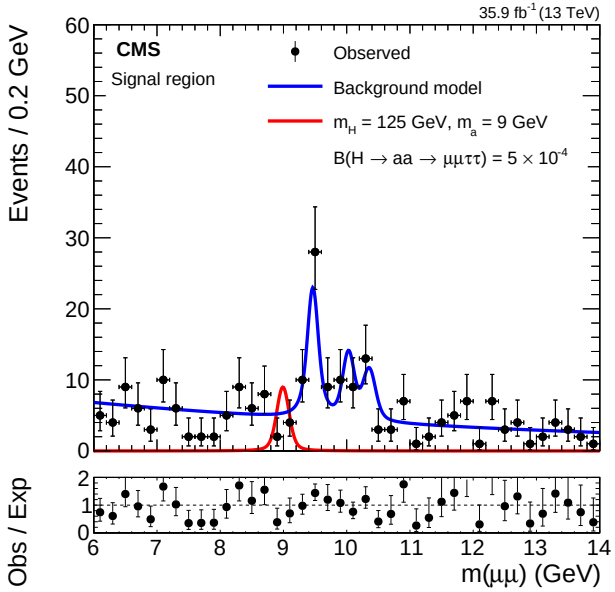
gluon gluon fusion



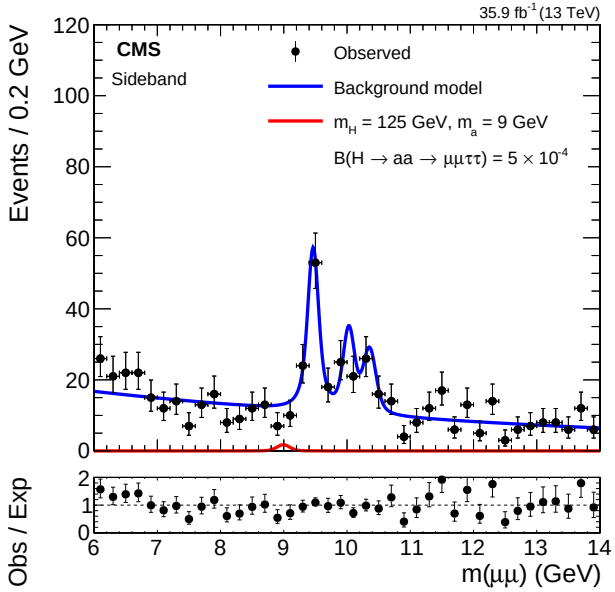
Data modeling: Fit 2D $m_{\mu\mu} \times m_{\mu\mu\tau_\mu\tau_h}$ (in 3 $m_{\mu\mu}$ bins)

- Signal: Voigtian $\times$ split normal distribution
- Bkg: exp. (continuum) + Voigtian (SM $\mu\mu$ resonances) $\times$ error function+exp.

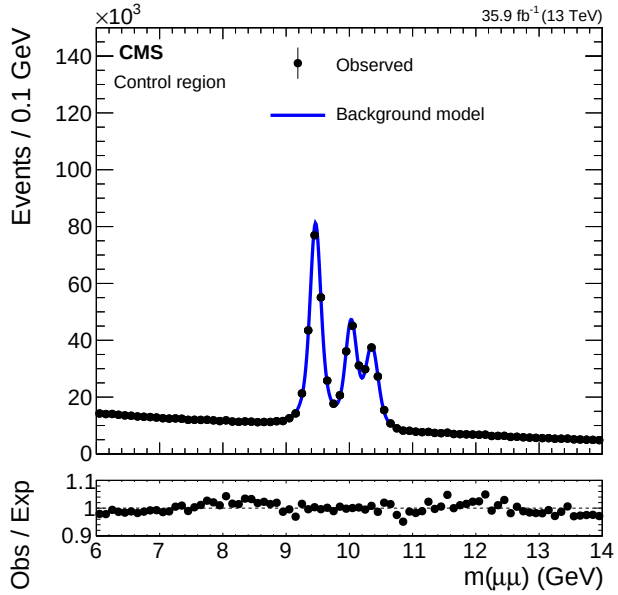
$m_{\mu\mu}$ in SR



$m_{\mu\mu}$ in Sideband

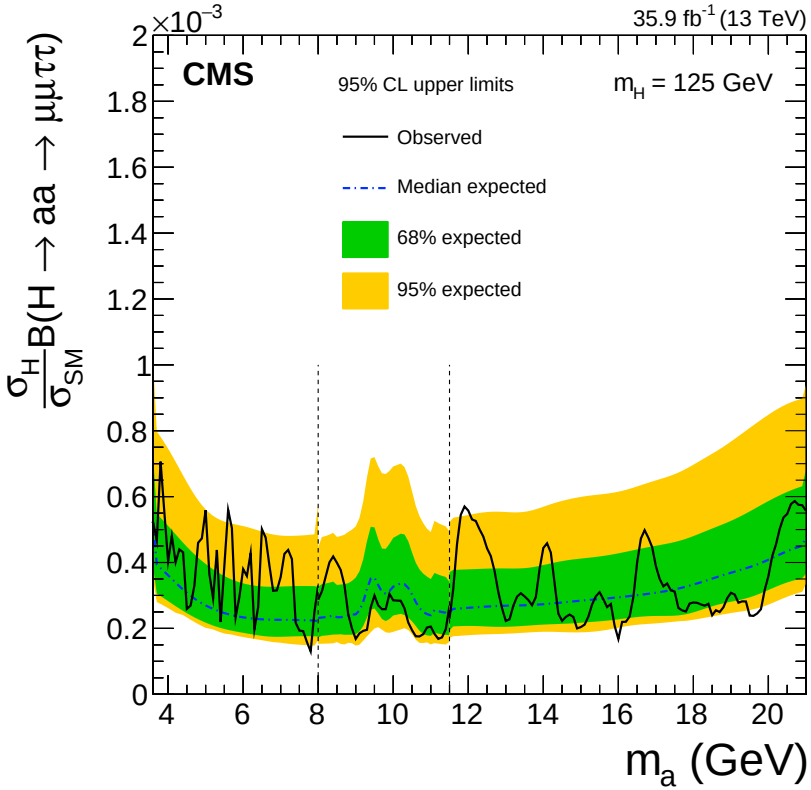


$m_{\mu\mu}$ in CR

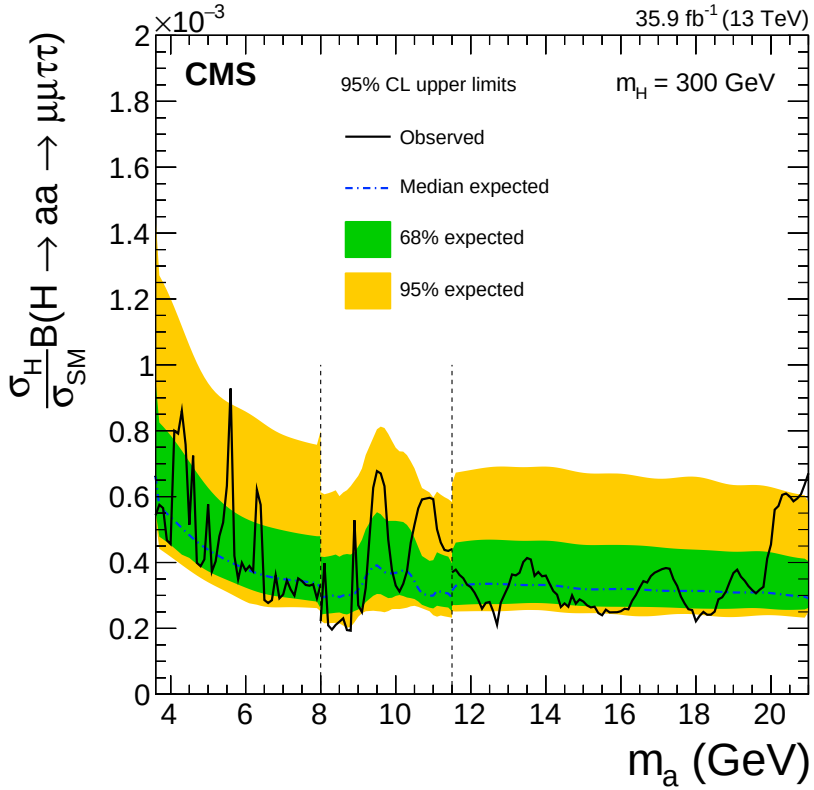


- Fit of 2D discriminant ($m_{\mu\mu}$,$m_{\mu\mu\tau_\mu\tau_h}$) is performed in 3 ranges of the $m_{\mu\mu}$
  - Simultaneous unbinned fit of SR, CR, Sideband
- No deviation from SM is observed
- Model-independent upper limits at 95% CL
- Model-specific limits (2HDM+S) extend earlier CMS and ATLAS searches

$m_H = 125$ GeV



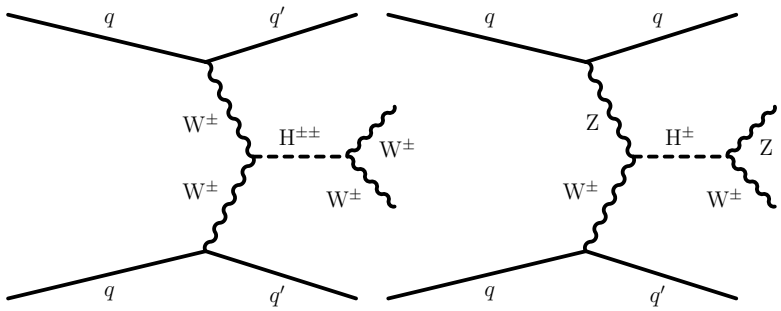
$m_H = 300$ GeV



Searches with full Run II data

$H^{\pm} \to W^{\pm}Z_0$ and $H^{\pm\pm} \to W^{\pm}W^{\pm}$ leptonic arXiv:2104.04762

- VBS production
- Leptonic final states characterized by:
  - $2\ell^{SS}$ or 3ℓ, p_T^{miss}, 2 jets (large $|\Delta\eta_{jj}|$, m_{jj})
- First results with 137 fb^{-1}



Background estimation

- Nonprompt lepton: from data with the "tight-to-loose" ℓ ratio, normalized in CR
- e sign misID: from simulation, applying data-to-sim efficiency correction (from $Z \to ee$ data)
- tZq and ZZ: from simulation, normalized in CRs
- WW and WZ: from simulation

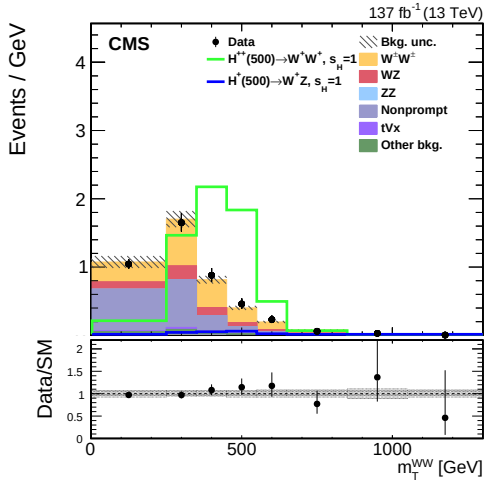
Signal extraction

- 2D final discriminant: (m_T^{VV}, m_{jj})

$$m_T^{VV} = \sqrt{(\sum_i E_i)^2 - (\sum_i p_{z,i})^2}$$

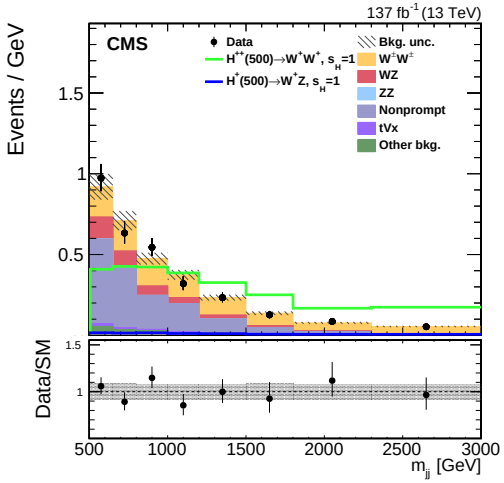
- Simultaneous fit of WW, WZ SR and the non-prompt lepton, tZq, and ZZ CRs.

m_T^{WW} in WW SR



- Discriminates signal from nonresonant bkg

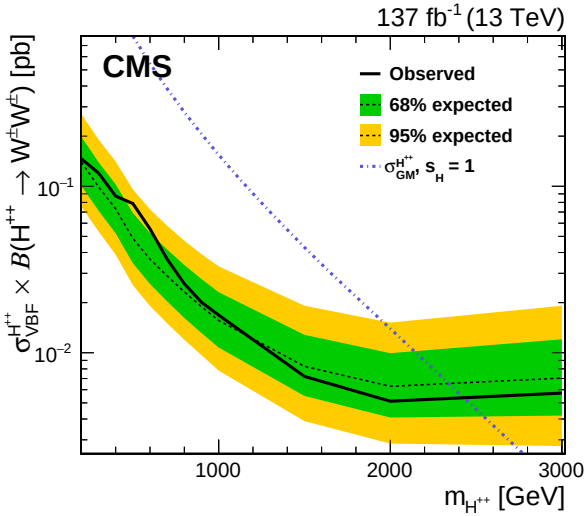
m_{jj} in WW SR



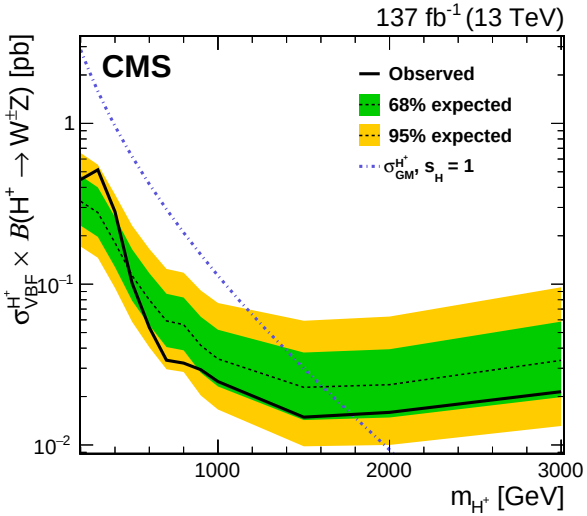
- Discriminates signal from non-VBS bkg

$H^{\pm} \to W^{\pm}Z_0$ and $H^{\pm\pm} \to W^{\pm}W^{\pm}$ leptonic arXiv:2104.04762

$H^{\pm\pm} \to W^{\pm}W^{\pm}$

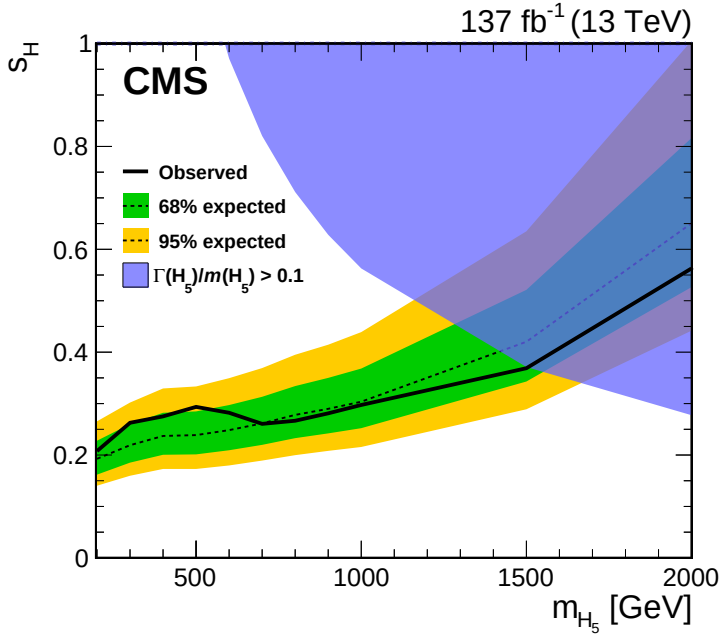


$H^{\pm} \to W^{\pm}Z^0$



- Model intepended exclusion limits at 95% CL
- Contribution of $H^{\pm}$ ($H^{\pm\pm}$) set to zero for the derivation of the limits on the $H^{\pm\pm}$ ($H^{\pm}$) production scenario
- Assuming $\Gamma_{H^{\pm}(\pm)} \lesssim 0.05 m_{H^{\pm}(\pm)}$

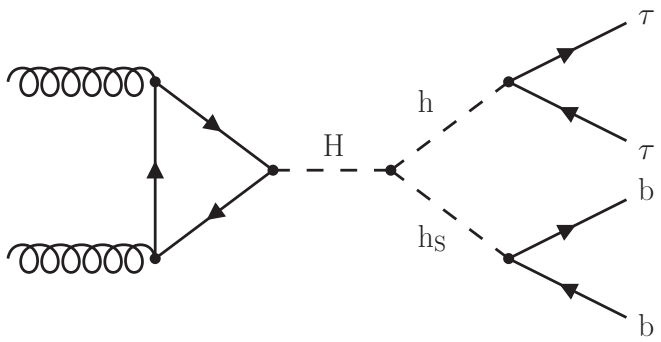
interpretation in GM model



Georgi-Machacek (GM) model:

- $H^{\pm\pm}$ and $H^{\pm}$ are degenerate in mass (m_{H_5})
- s_H^2: fraction of the m_W^2 generated by the vev of the triplet field
- Simultaneous contribution of $H^{\pm\pm}$ and $H^{\pm}$
- Theoretically inaccessible parameter space
- $s_H >$ 0.20-0.35 excluded for $m_{H_5} =$ 200-1500 GeV
- Sensitivity improvement wrt previous CMS results

- Gluon fusion production
  - $h_S \to bb$ LARGE BR
  - $h(125) \to \tau\tau$: CLEAN SIGNATURE
- 3 final states $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$ characterized by:
  - $1\ell 1\tau_h$ or $2\tau_h$ (OS, large ΔR), $\geq$2 jets, $\geq$ 1 b jet
- Main background: $t\bar{t}$, QCD, Z, Diboson, W+jets



Background estimation

- Genuine $\tau\tau$: τ-embedding (from $\mu\mu$ events, μ energy deposits replaced by simulated τ)
- $j \to \tau_h$: Fake factors applied in orthogonal region with looser τ_h ID
- Z, $t\bar{t}$, Diboson decaying to ℓ: from simulation

Event classification

- Events categorization based on NN multiclassification (s+4b classes):

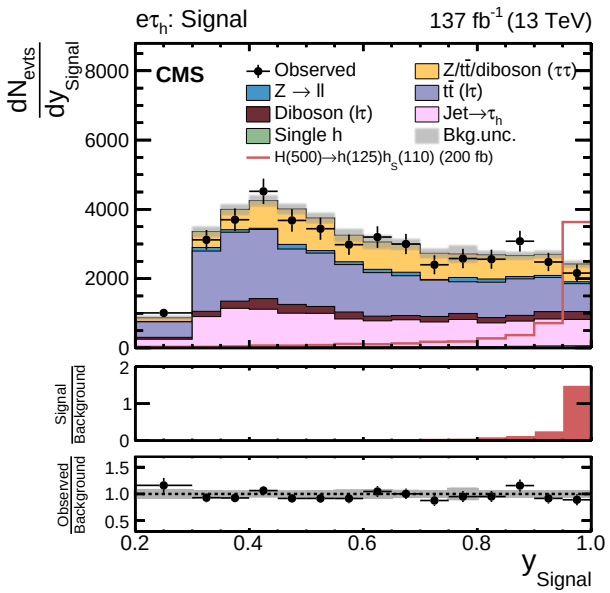
  (1) "$\tau\tau$" (2) "jet $\to$ τ_h" (3) "$t\bar{t}$" (4) "misc" (5) "signal"

- 68 NNs per category trained with different groups of m_H and m_{h_S}
- In total 45 categories: 3 years $\times$ 3 FS $\times$ 5 classes

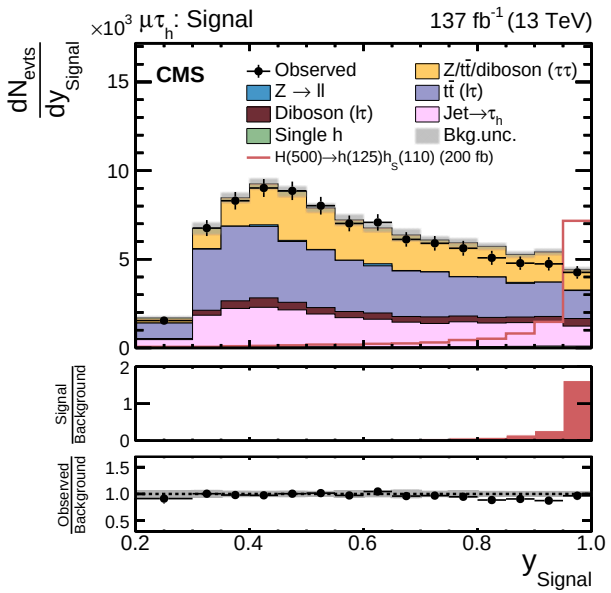
Signal extraction

- The NN score for the 45 event categories is used as a final discriminant
  - The fit is done for each of the 68 trainings independently
  - Background categories are used to constrain the background nuisance parameters

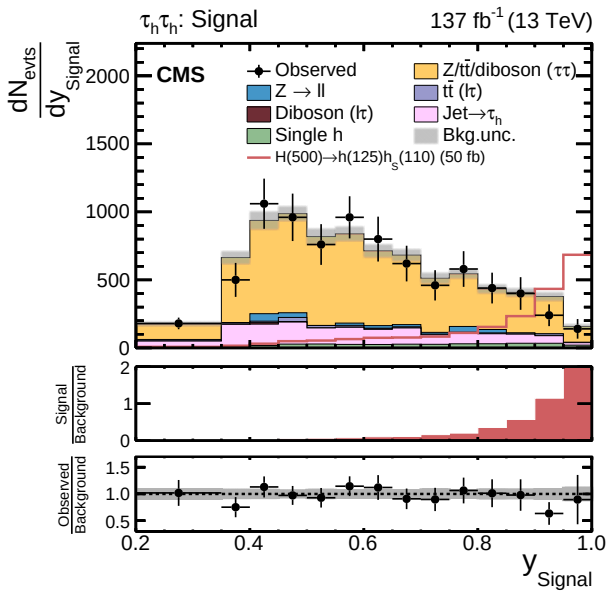
$e\tau_h$,"signal"



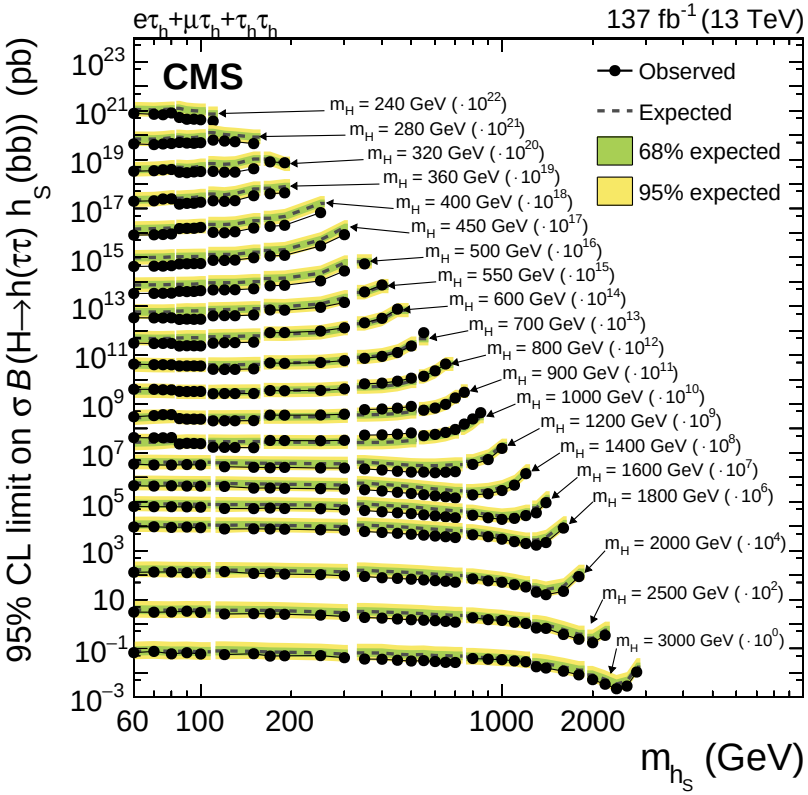
$\mu\tau_h$,"signal"



$\tau_h\tau_h$,"signal"

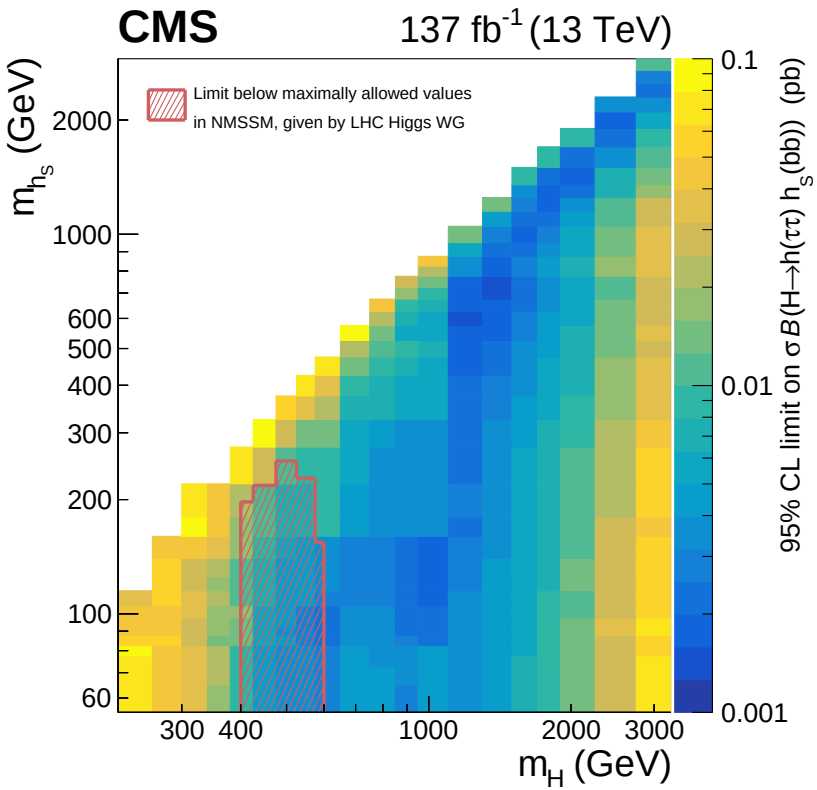


Model independent upper limits at 95% CL



- Limits for each m_H scaled by orders of 10

Summary of observed limits



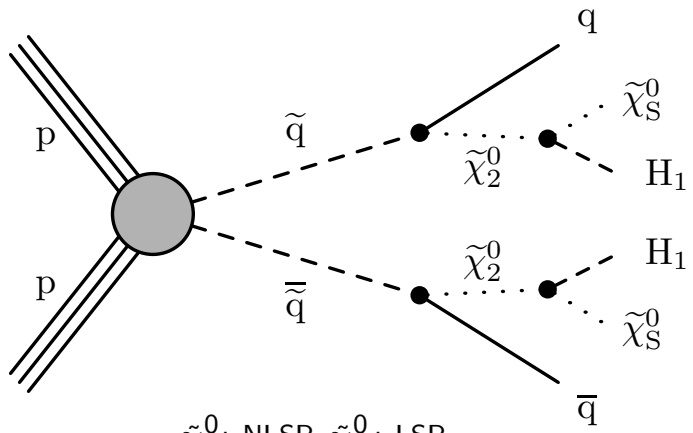
- Maximally allowed values in NMSSM shown

- Upper limits of 125–2.7 fb for m_H = 240-1000 GeV
- No deviation from SM observed
- First LHC search of the process

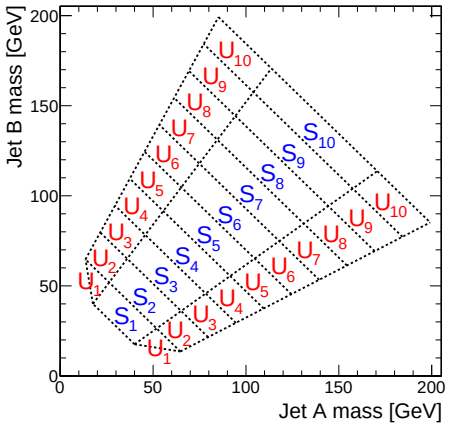
Light H from SUSY cascade decays $H_1H_1 \rightarrow$ bbbb CMS-PAS-HIG-20-018

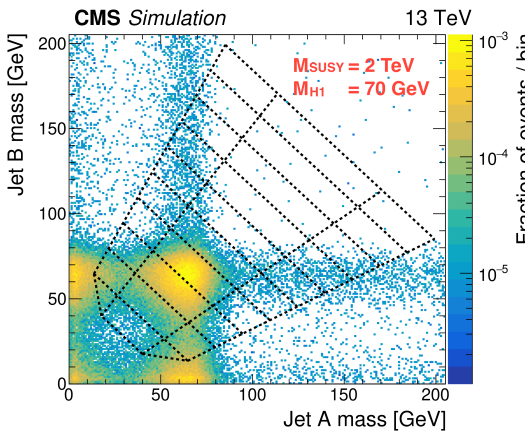
- Focus on an CP-even singlet-like Higgs boson
- Assuming mass-degenerated squarks with $M_{SUSY} > 1200$ GeV, $M_{H_1}/M_{\tilde{\chi}_2^0} = 0.99$ **BOOSTED H_1**
- $M_{H_1} < M_Z$ **Large BR To bb**
- Final state $H_1H_1 \rightarrow$ bbbb characterized by:
  - low p_T^{miss}, large H_T
  - ≥ 2 large-R double b-tagged jets ($H_1 \rightarrow$ bb)
  - ≥ 1 jet (quarks from squark decays)
- Main background: $t\bar{t}$, QCD multijet, V+jets

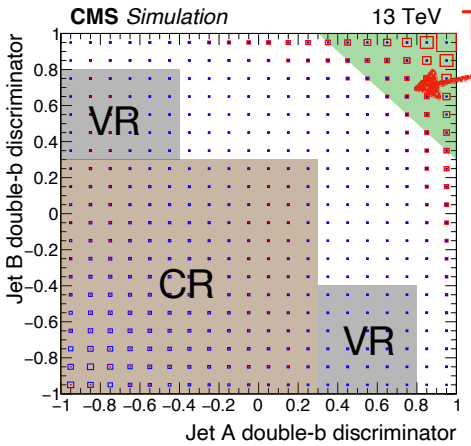
Production of H_1 pair



$\tilde{\chi}_2^0$: NLSP, $\tilde{\chi}_S^0$: LSP







Double b-tag regions

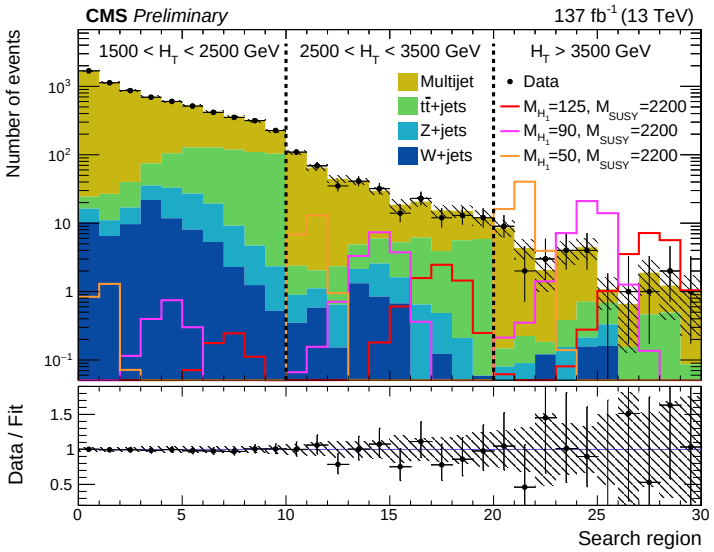
- 10 signal regions S_i and 10 sideband regions U_i in the 2D parameter space of the large-R jets' soft drop mass

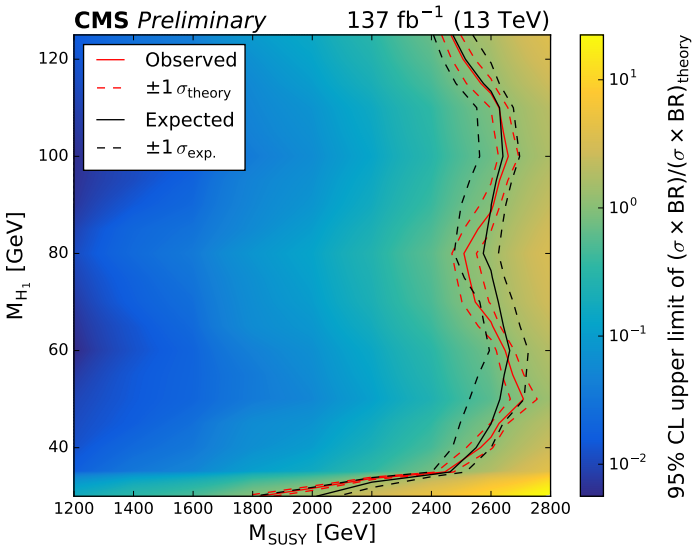
- **Multijet bkg estimation:** $\hat{S}_i^{TR} = F_i \cdot \hat{U}_i^{TR}$
- $F_i = S_i/U_i$ in CR
- Validated in VR

Light H from SUSY cascade decays $H_1H_1 \rightarrow$ bbbb CMS-PAS-HIG-20-018

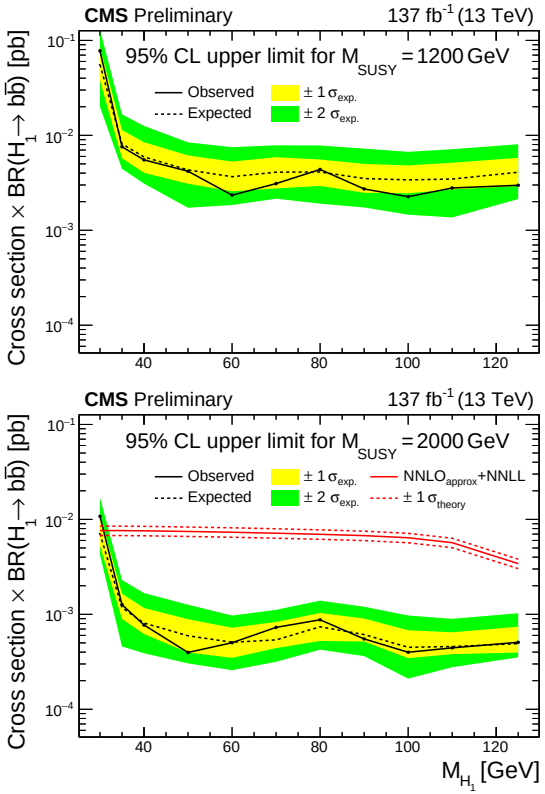
- 3 H_T bins with 10 S_i regions distribution:

Post fit SR yields





Limits for constant M_{SUSY}



Results compared with benchmark model

- Observed 95% CL upper limits of $(\sigma \times BR)/(\sigma \times BR)_{theory}$
- $1200 \leq M_{SUSY} \leq 2500$ GeV within $40 \leq M_{H_1} \leq 120$ GeV are excluded

Summary

Latest searches for BSM Higgs bosons at CMS have been presented

- New unexplored signal signatures
- First results with Run II data collected by the CMS detector during 2016-2018
- Significant imrovements wrt previous results - Large part of parameter space excluded
- No evidence for BSM physics observed

- More results to come with Run II data!

Thank you!

ACKNOWLEDGMENT

This work was co-funded by the European Regional Development Fund and the Republic of Cyprus through the Research Promotion Foundation under the projects **POST-DOC/0718/0169** and **EXCELLENCE/1918/0379**

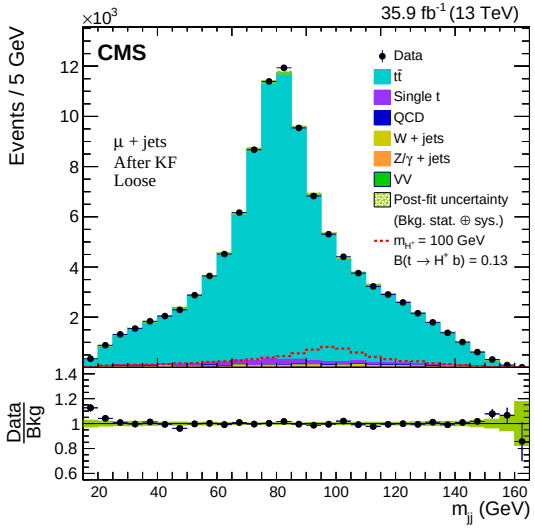
BACKUP

c-tagging efficiency

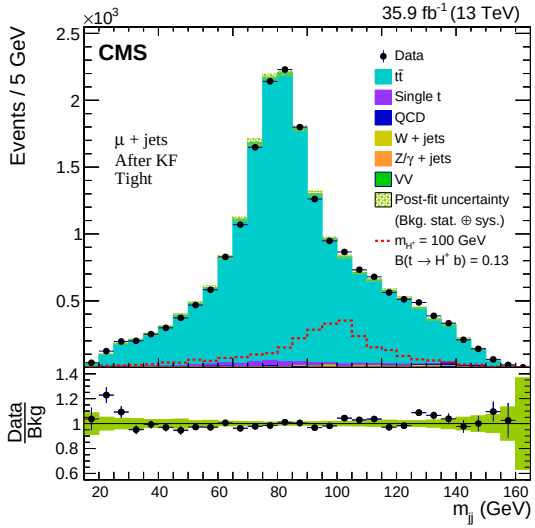
Working point	ϵ^{c} (%)	ϵ^{b} (%)	ϵ^{udsg} (%)
Loose	88	36	91
Medium	40	17	19
Tight	19	20	1.2

- Model-independent upper limits for the individual final states, after combining the c-tagging categories

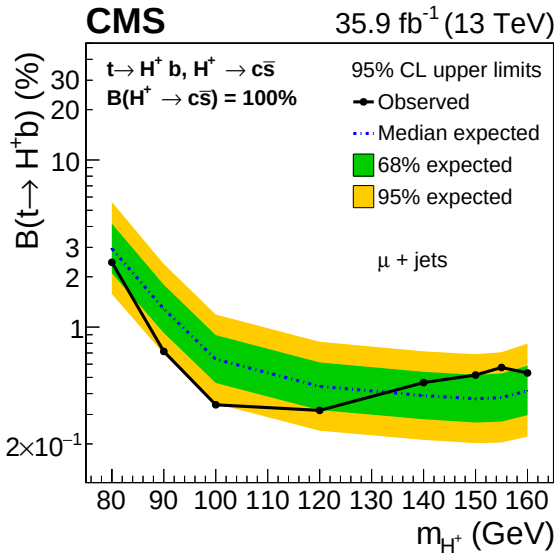
μ+jets, Loose c-tagging



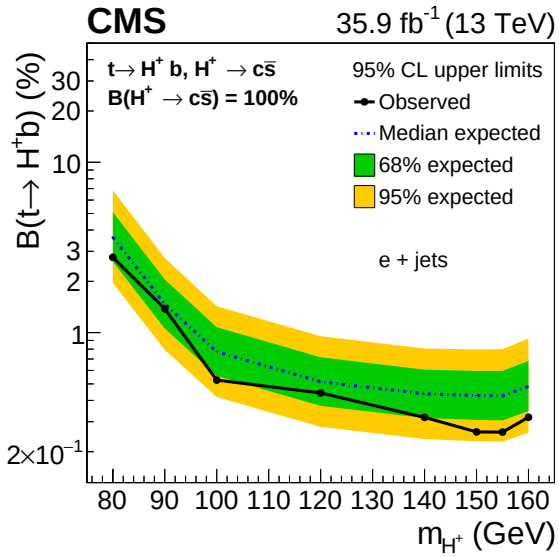
μ+jets, Tight c-tagging



limits of 2.44-0.32% (μ+jets)



limits of 2.77-0.26% (e+jets)



Data modeling: Fit 2D $m_{\mu\mu} \times m_{\mu\mu\tau_\mu\tau_h}$ (in 3 $m_{\mu\mu}$ bins)

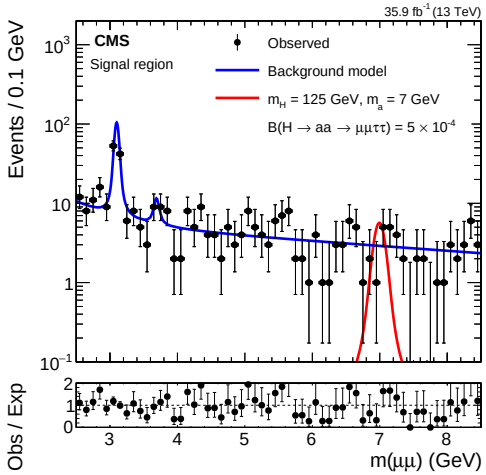
- Signal: Voigtian $\times$ split normal distribution
- Bkg: exp. (continuum) + Voigtian (SM $\mu\mu$ resonances) $\times$ error function+exp.

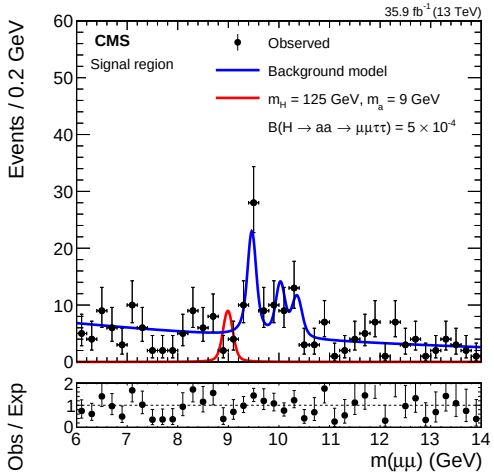
$2.5 \leq m_{\mu\mu} \leq 8.5$ GeV

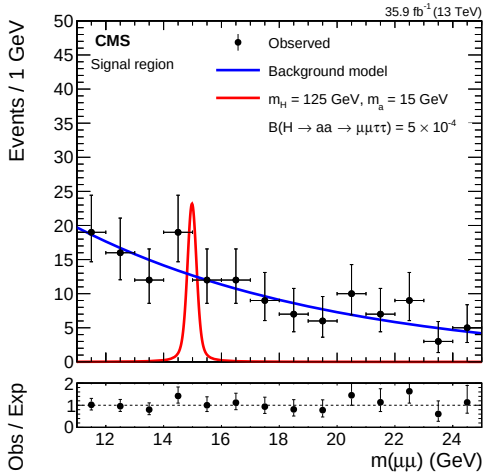
$6 \leq m_{\mu\mu} \leq 14$ GeV

$11 \leq m_{\mu\mu} \leq 25$ GeV

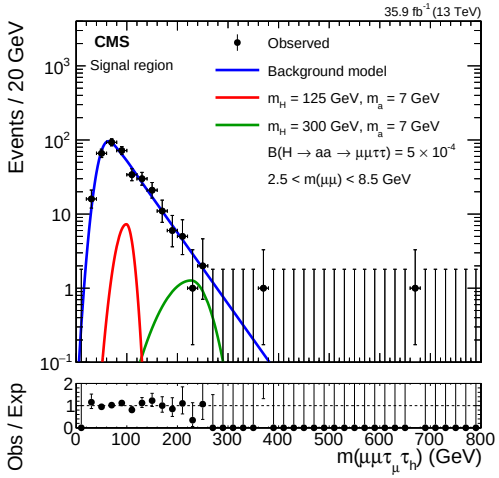
SR, $m_{\mu\mu}$

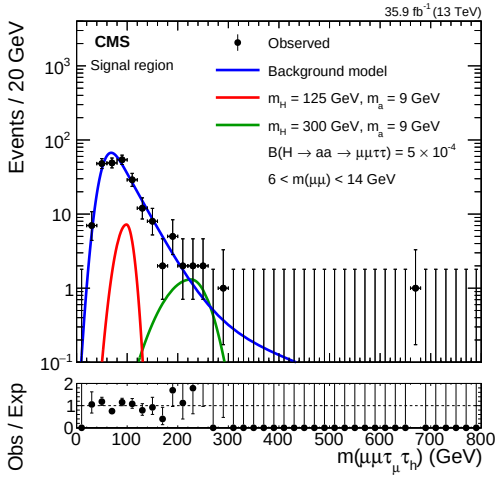


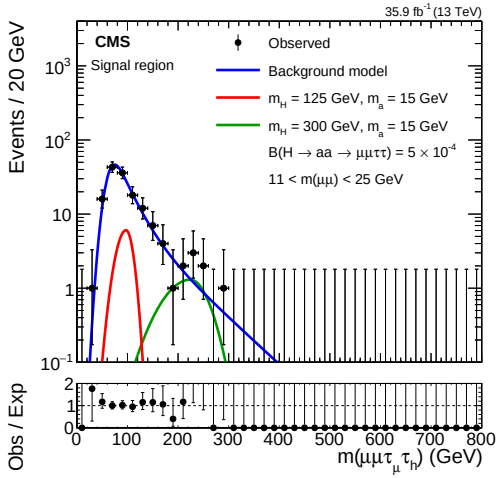




SR, $m_{\mu\mu\tau_\mu\tau_h}$



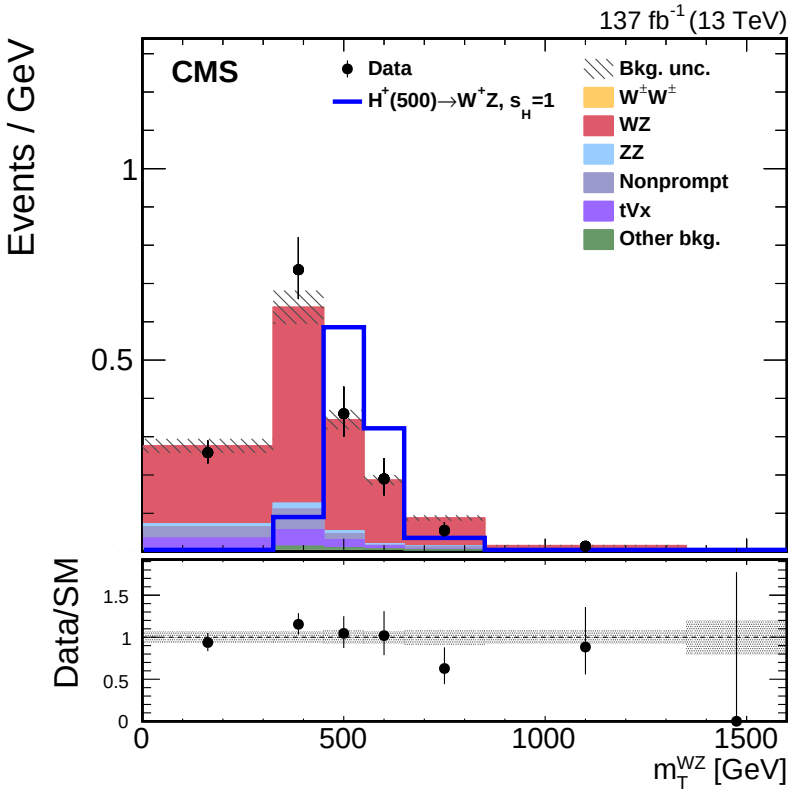




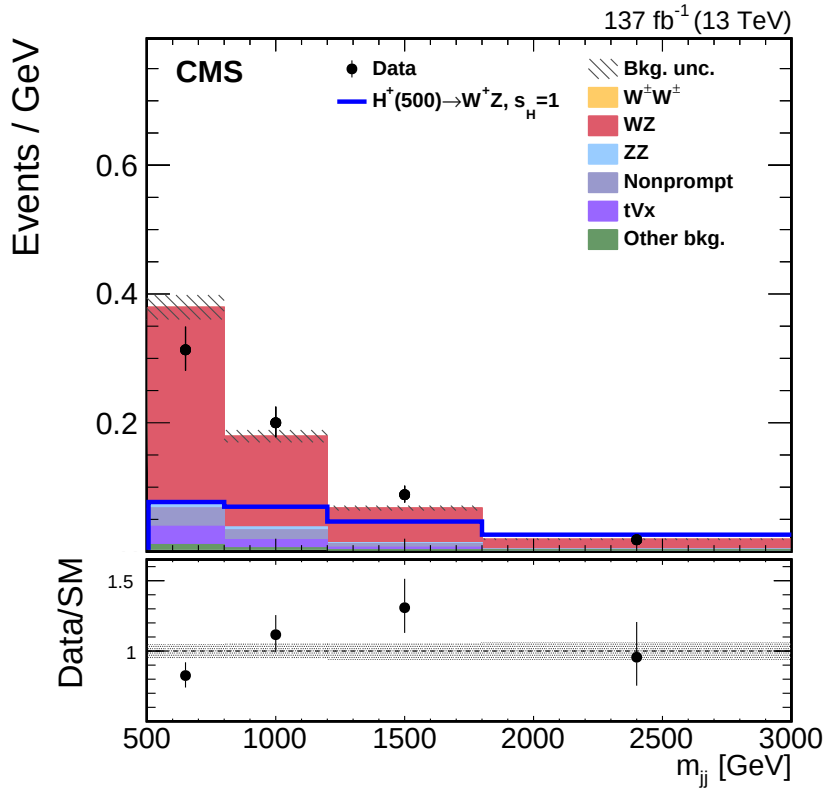
Signal extraction

- Final discriminant is the 2D distribution: (m_T^{VV}, m_{jj})
- Simultaneous fit of WW and WZ SR

m_T^{WZ} in WZ SR



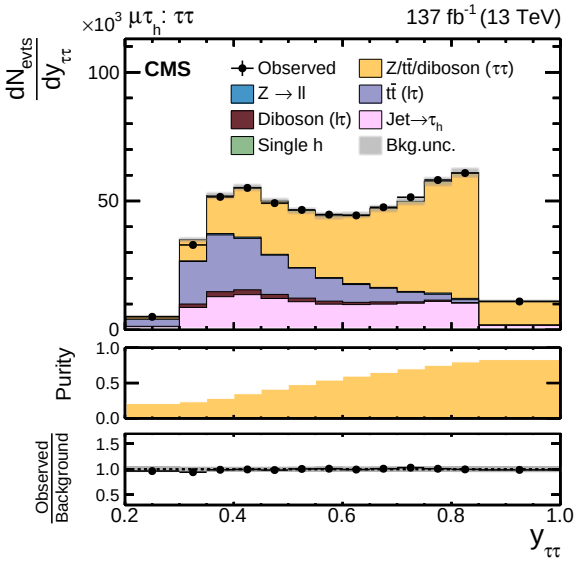
m_{jj} in WZ SR



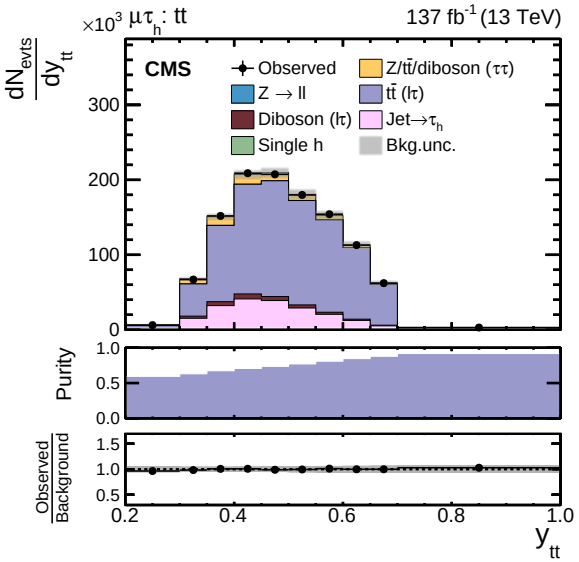
- Discriminates resonant signal from nonresonant background
- Discriminates signal from non-VBS processes

- NN score of the 4 background classes for the $\mu\tau_h$ final state

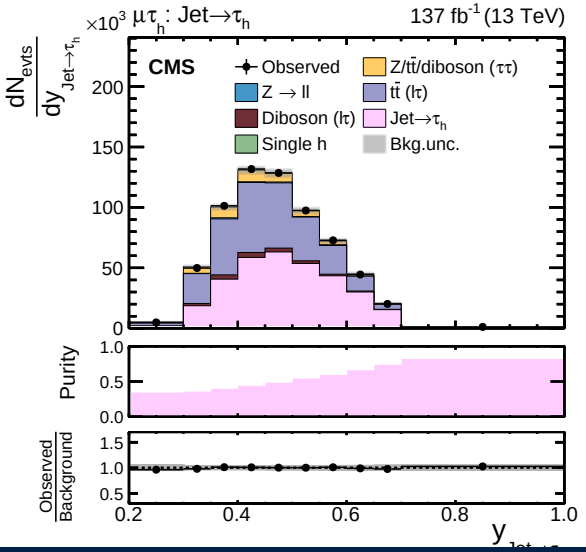
$\mu\tau_h$,"$\tau\tau$"



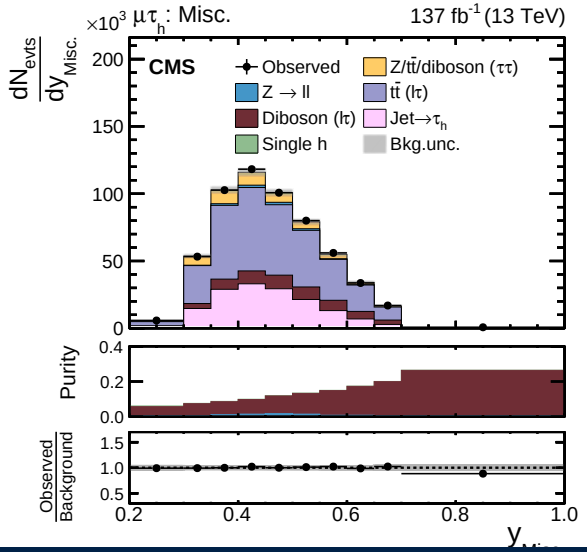
$\mu\tau_h$,"$t\bar{t}$"



$\mu\tau_h$,"jet $\to$ τ_h"



$\mu\tau_h$,"misc"



- Good separation and high purity of the correct bkg class as the NN score increases
- Background categories are used by the fit to constrain the background nuisance parameters