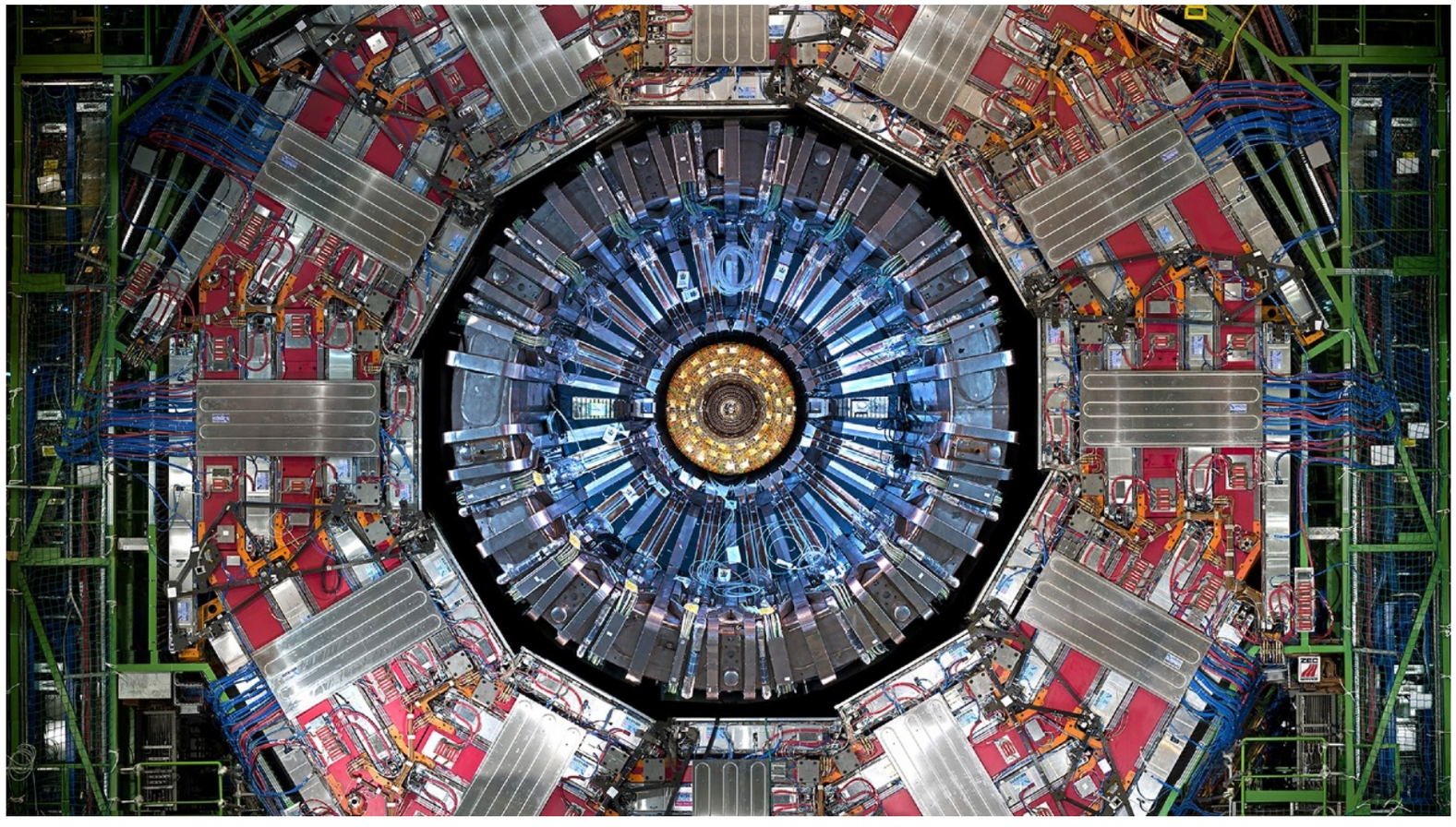
Imperial College London

Searches for Extended Higgs Sectors at CMS



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ICHEP2022 conference
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Introduction

- Today I present the latest results by the CMS Collaboration in search for additional charged and neutral Higgs bosons

- Lots of searches performed by CMS in many final states

- Will focus today on very latest results from this year

- Note I will not cover H(125)→aa searches as these are covered in the next talk by Khawla Jaffel

- All results shown today utilise the 138 fb^{-1} 13 TeV dataset collected by CMS between 2016—2018

Motivations

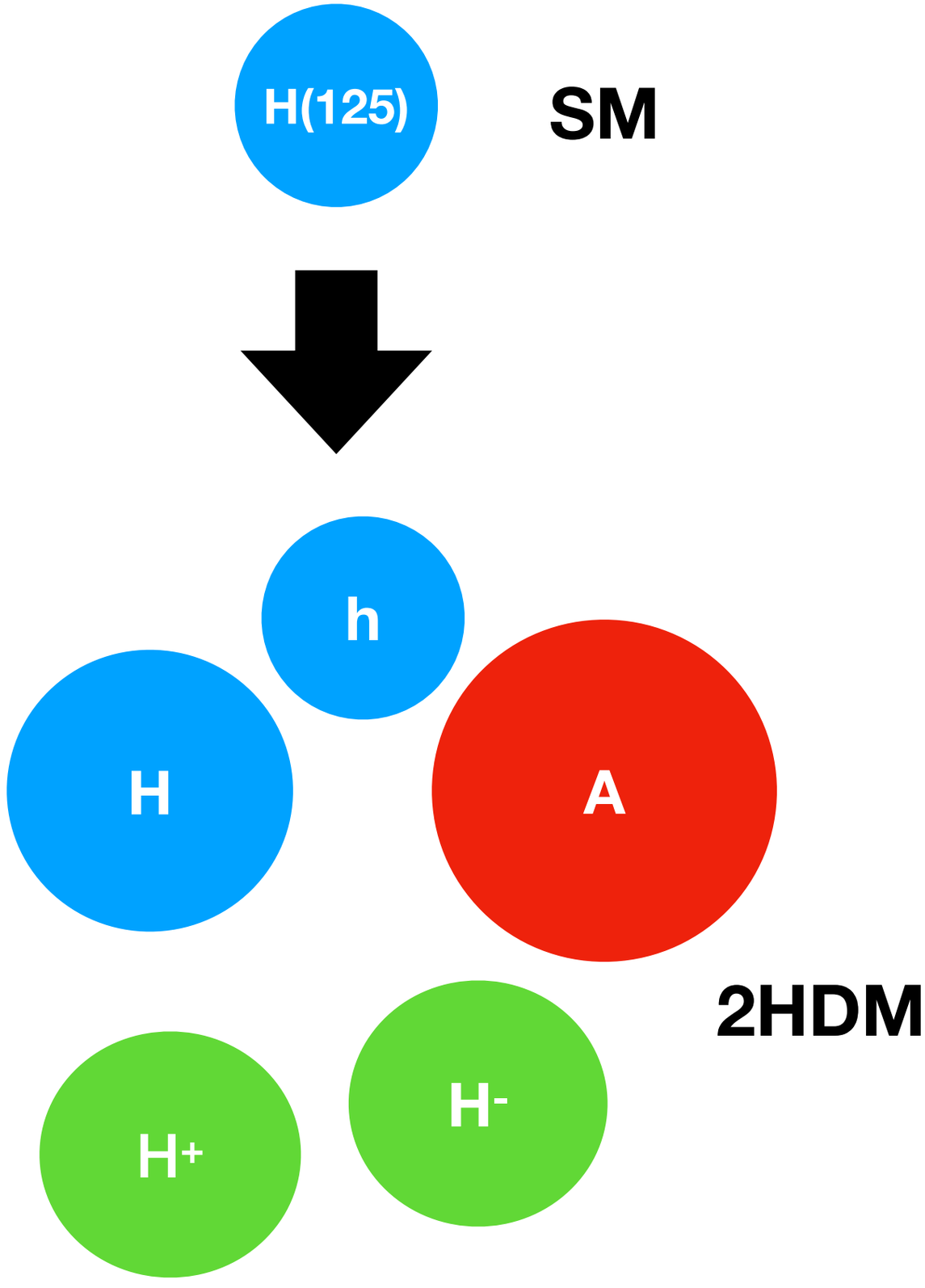
- After spontaneous symmetry breaking SM Higgs sector has one DOF = SM Higgs Boson H(125)

- Extended Higgs sectors may contain additional Higgs doublets and/or singlets

- Additional degrees of freedom = additional Higgs bosons

- E.g 2 Higgs doublet model (2HDM) has 3 neutral bosons (h, H, A), and 2 charged Higgs ($H^{\pm}$)

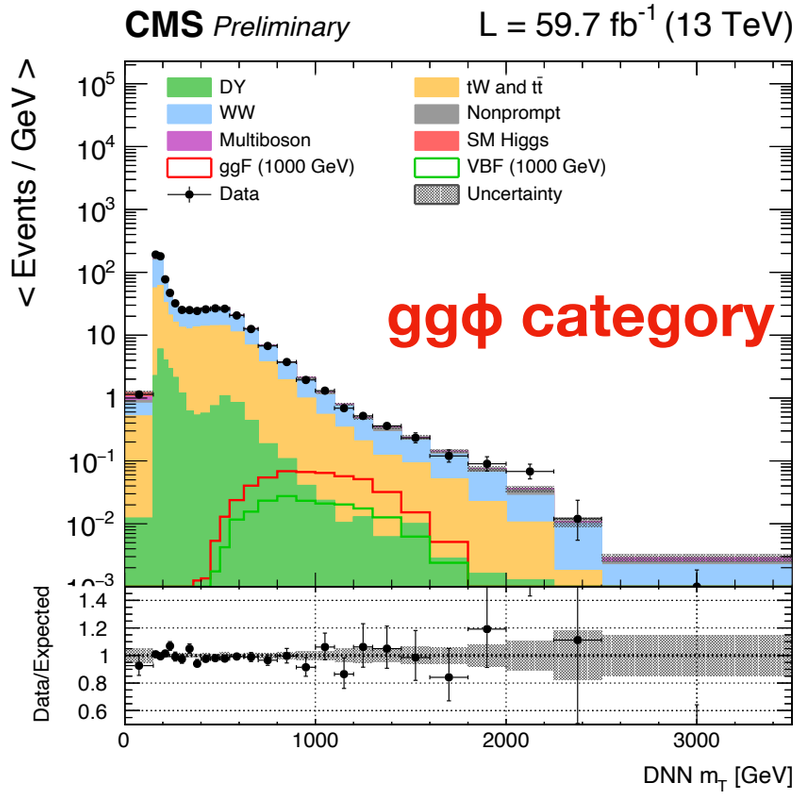
- We can search for these additional spin-0 particles at the LHC



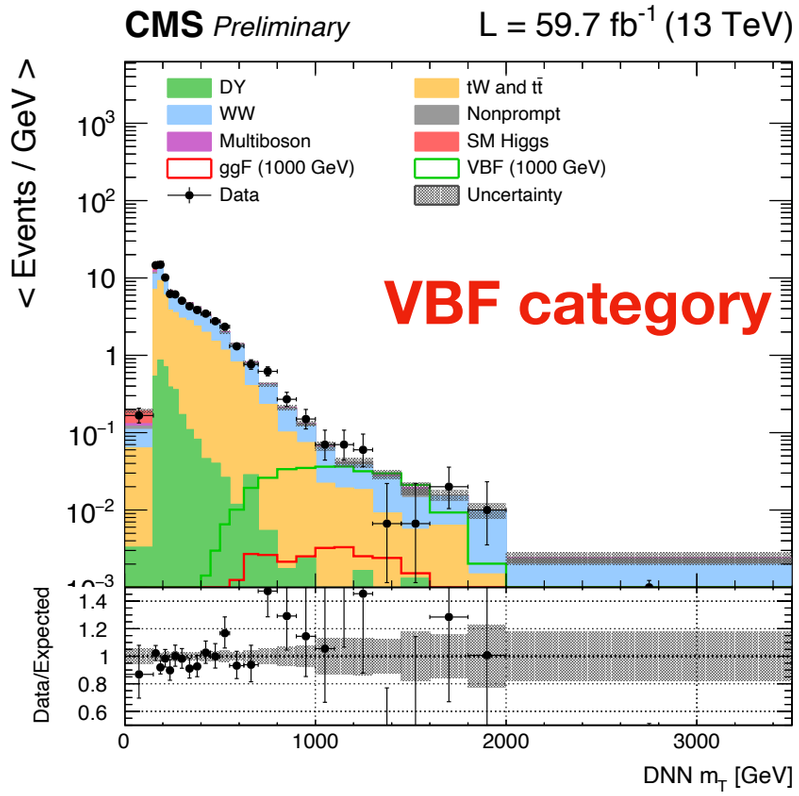
Neutral Higgs

H→WW

- Search for H decaying into WW in mass range 115 GeV — 5 TeV
  - Leptonic final states considered: eμ, μμ, ee
  - Production by gluon fusion (ggϕ) and VBF
- Low and high (> 1 TeV) mass search strategies



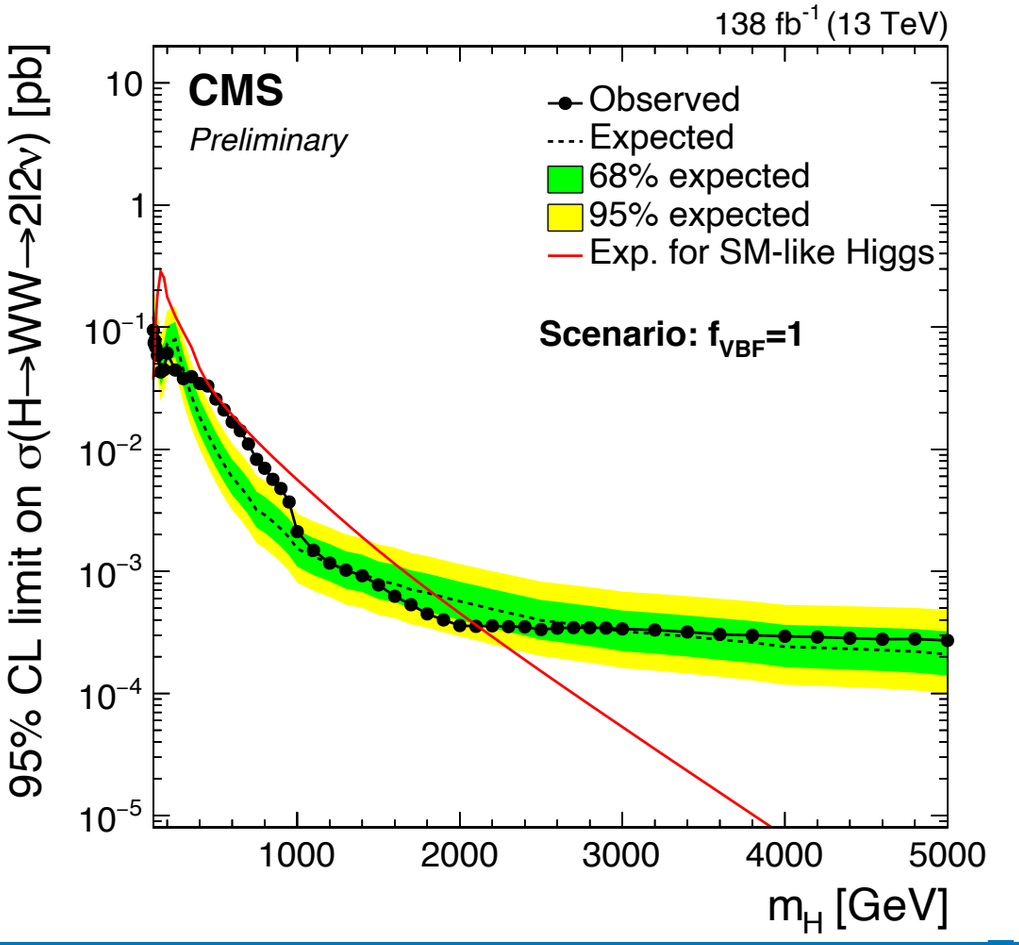
- For high mass W's are boosted and therefore back-to-back
- Deep neural network (DNN) separates background, ggϕ, and VBF
- DNN regresses H mass which is fitted to extract results

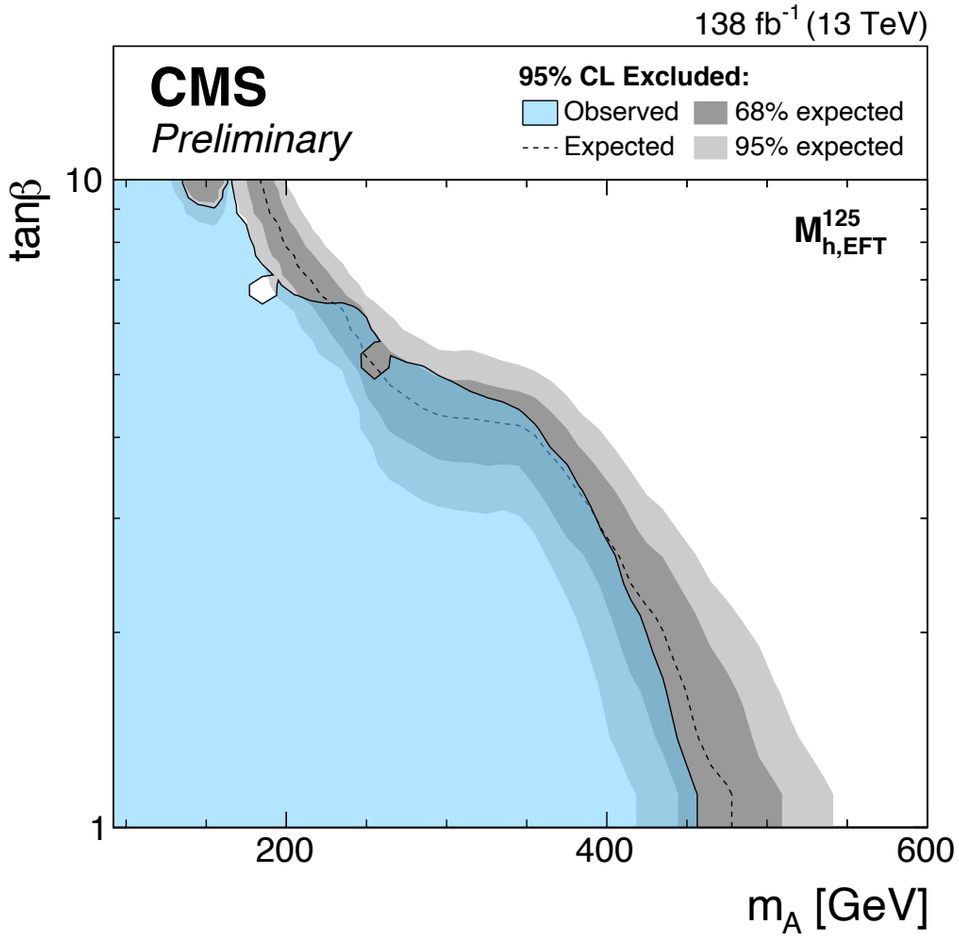


HIG-20-016

H→WW: Results

- Several width hypotheses considered range from 0.1—10%
- Interference effects between background and signal accounted for via reweighing (MELA)
- Limits presented on cross-sections for different assumption for VBF fraction (f_{VBF})
- Excess in mass region ~ 650—800 GeV, largest local (global) significance for VBF [f_{VBF}=1] @ 650 GeV → 3.8 (2.6)σ
- Largest excess for ggϕ @ 950 GeV → 2.6 (0.4)σ
- Interpretations in 2HDMs and MSSM

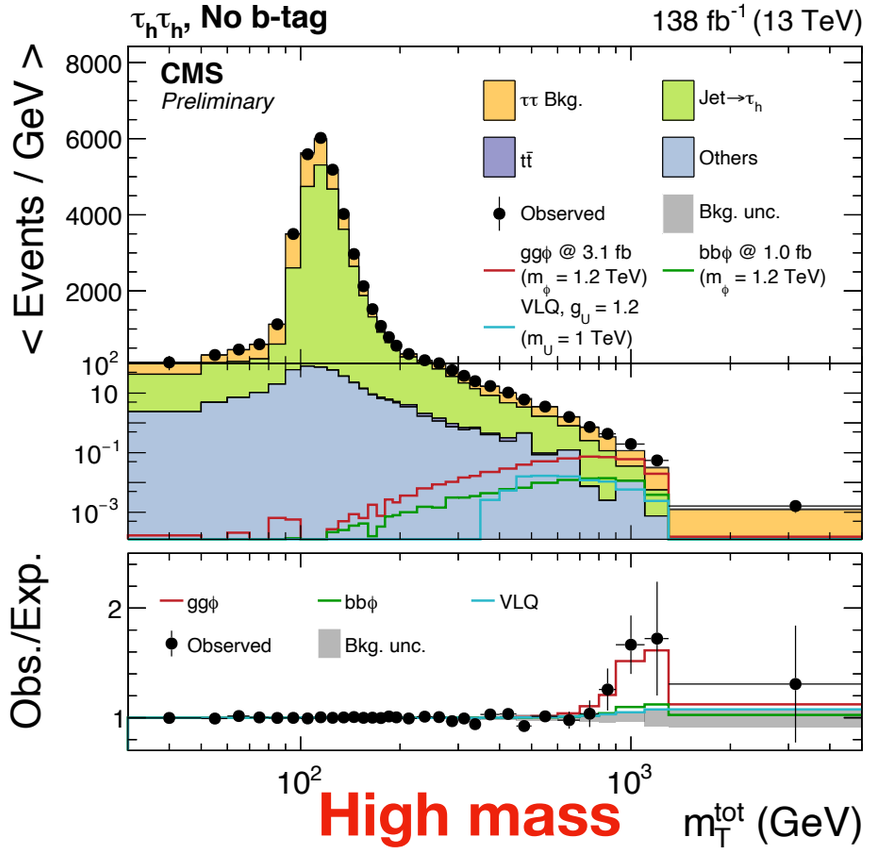




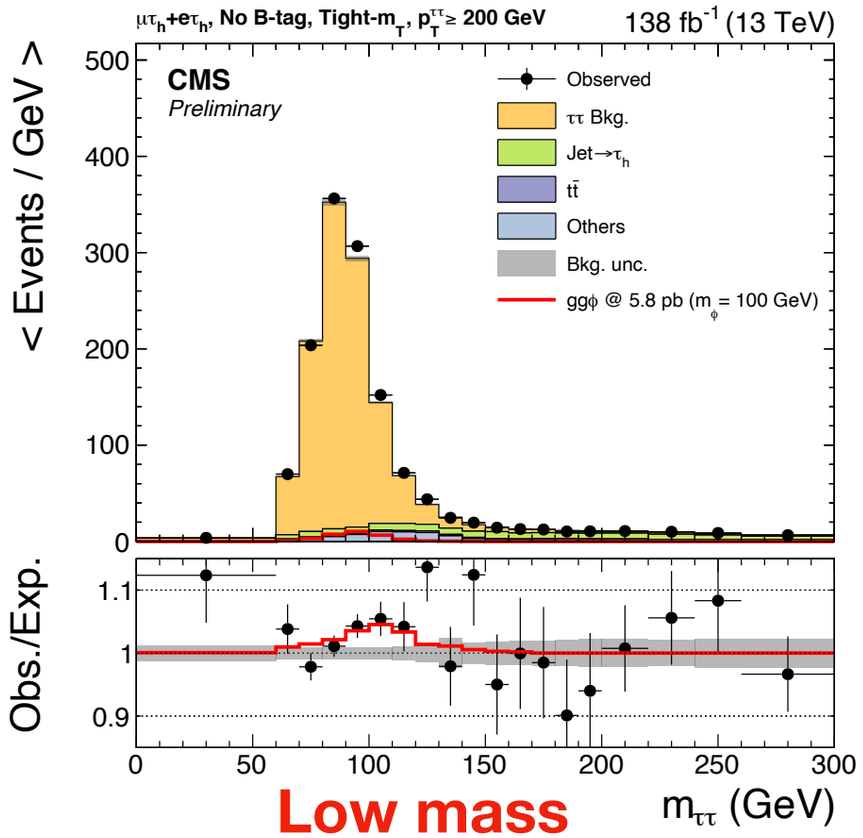
HIG-20-016

H/A→$\tau\tau$

- Search for H/A production via ggϕ and b-associated production (bbϕ) in mass range 60 GeV — 3.5 TeV
  - Target using 0 and >0 b-jet categories
- 4 most sensitive $\tau\tau$ final states: $\tau_h\tau_h$, μτ_h, eτ_h, eμ
- Analysis split into high and low mass search regions
  - Fit total transverse mass (m_T^{tot}), for high mass and di-τ mass ($m_{\tau\tau}$) for low mass



High mass

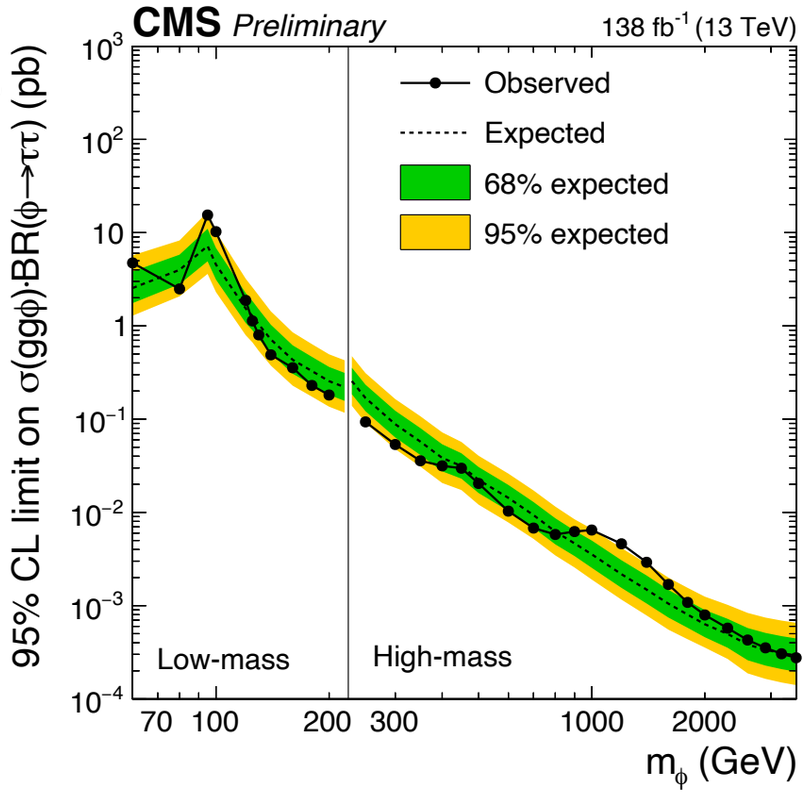


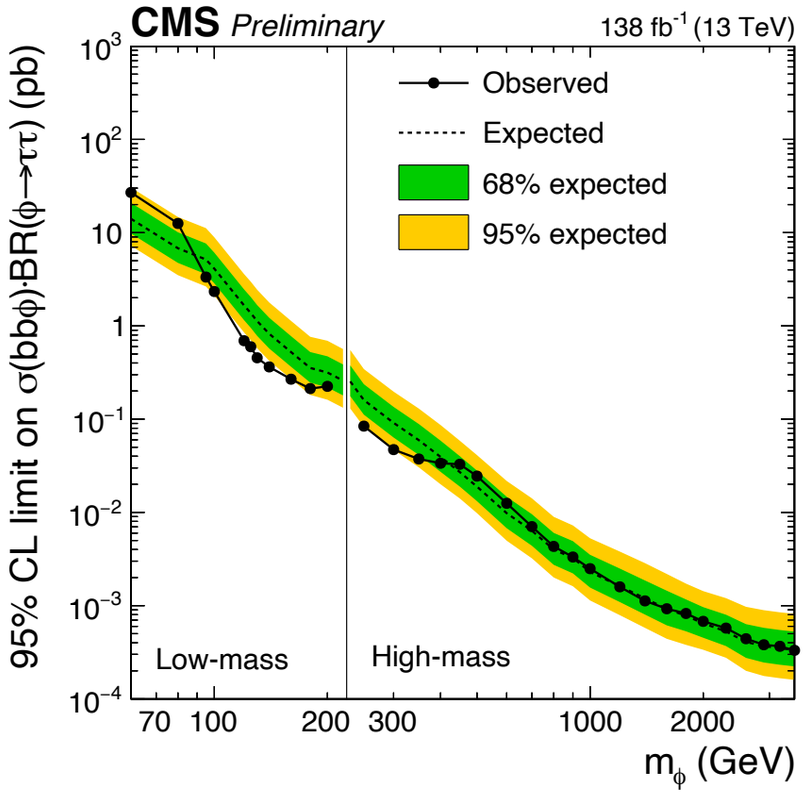
Low mass

HIG-21-001

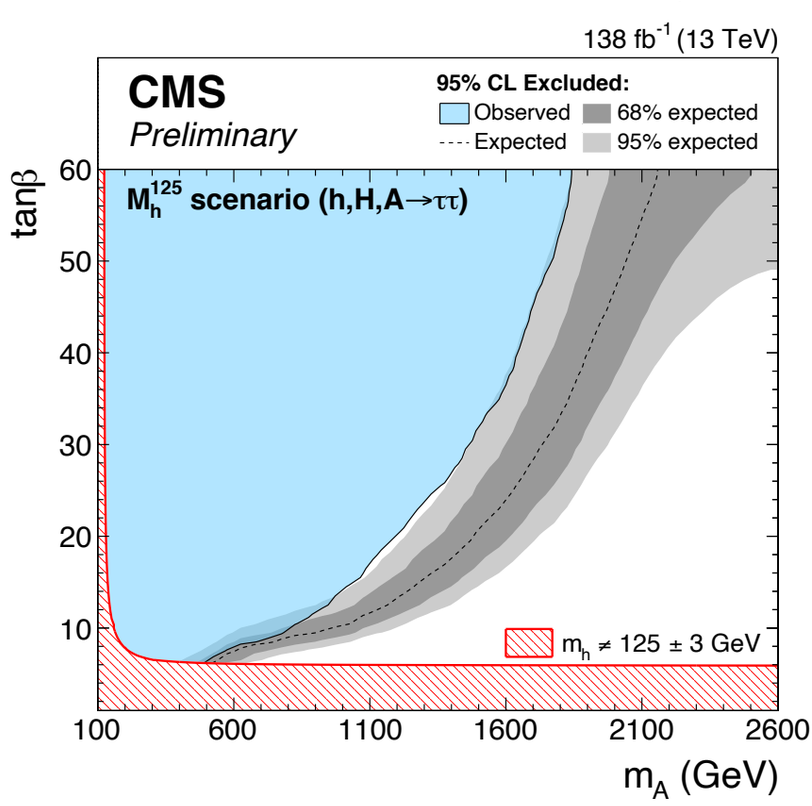
H/A→ττ: Results

- Two excesses observed for ggϕ at 100 GeV and 1.2 TeV
  - Local (global) significance = 3.1 (2.7)σ @ 100 GeV
  - 2.8 (2.4)σ @ 1.2 TeV
  - Note global significance only accounts for the low (high) mass search range





- Limits set on cross-sections for ggϕ and bbϕ
- Results interpreted in MSSM benchmark scenarios and vector-leptoquark models

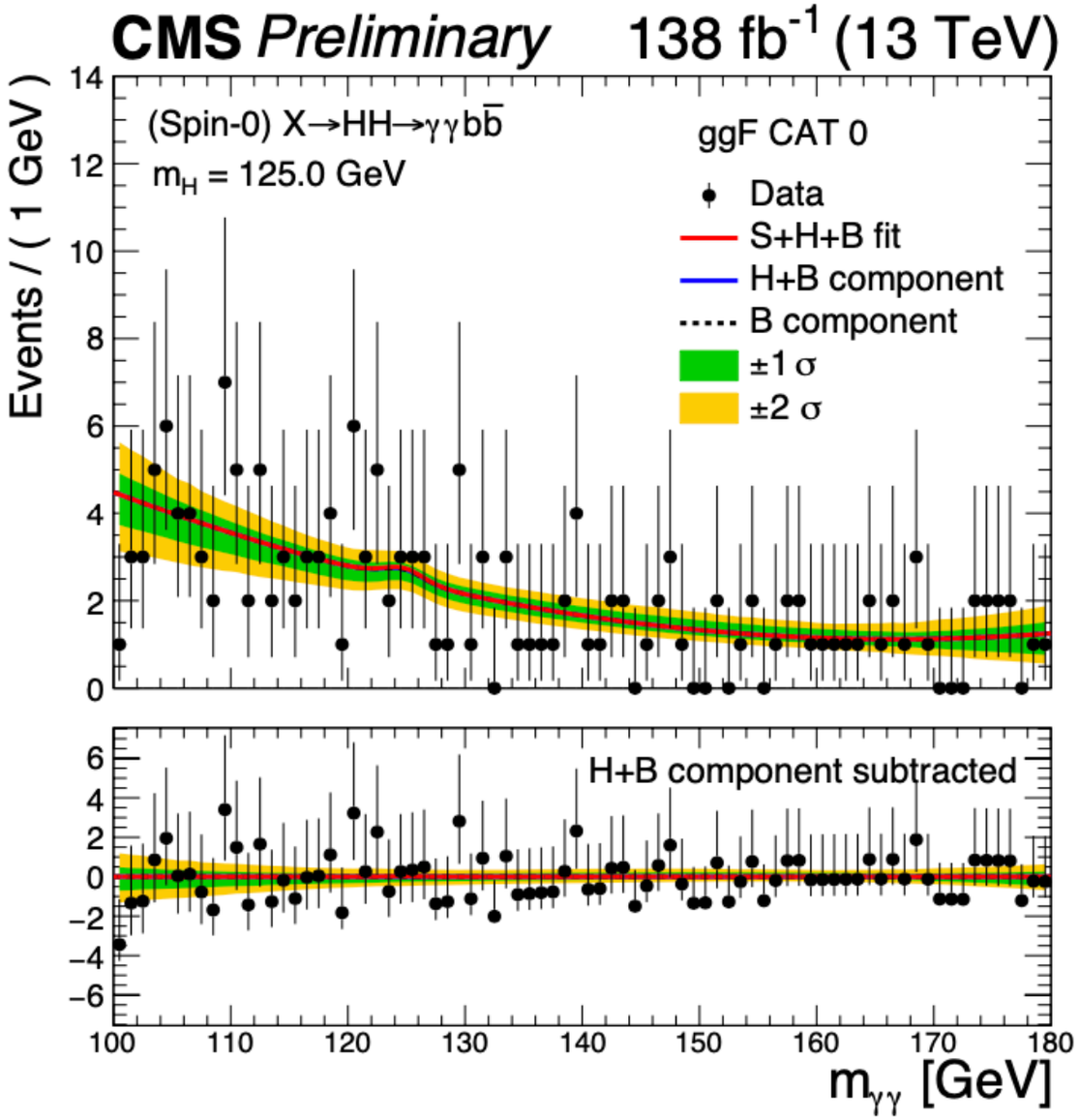


HIG-21-001

H→hh(Yh)→bbɣɣ

New!

- NN to reject ttH background
- BDT to reject non-resonant ɣ(ɣ)+ jets background
- B jets tagged using DNN (“DeepJet”)
- $\widetilde{M}_X$ variable used to select events in a window close to m_H
  - $\widetilde{M}_X = m_{\gamma\gamma jj} - (m_{\gamma\gamma}-m_H) - (m_{jj} - m_{H,Y})$
- 2D fit of $m_{\gamma\gamma}$ vs m_{jj}



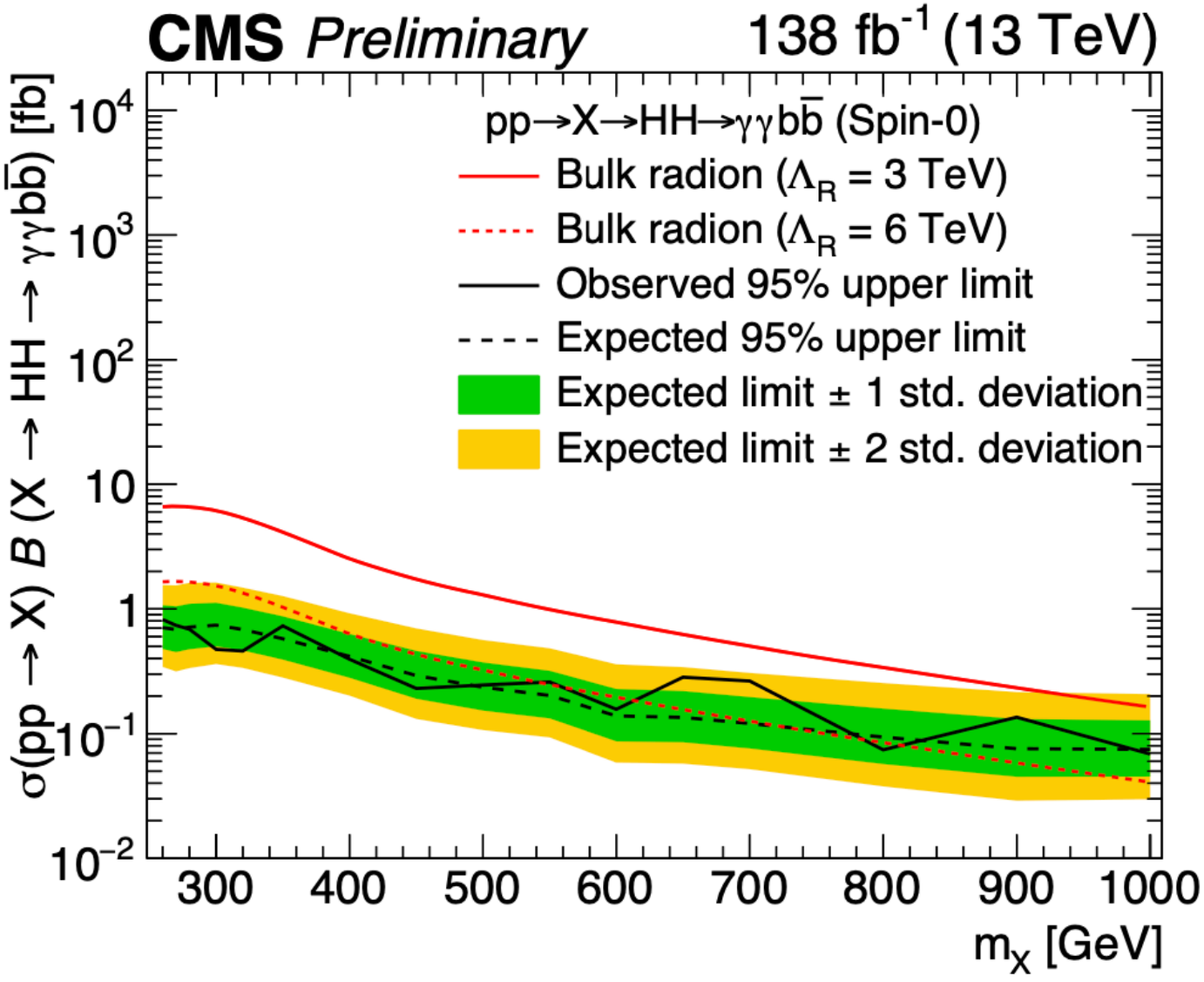
HIG-21-011

H→hh→bbɣɣ

New!

- No statistically significant excesses observed

- Limits set of cross sections times branching fractions



HIG-21-011

(Results in bbbb (boosted) and bbWW final state in backup)

H→Yh→bbɣɣ

New!

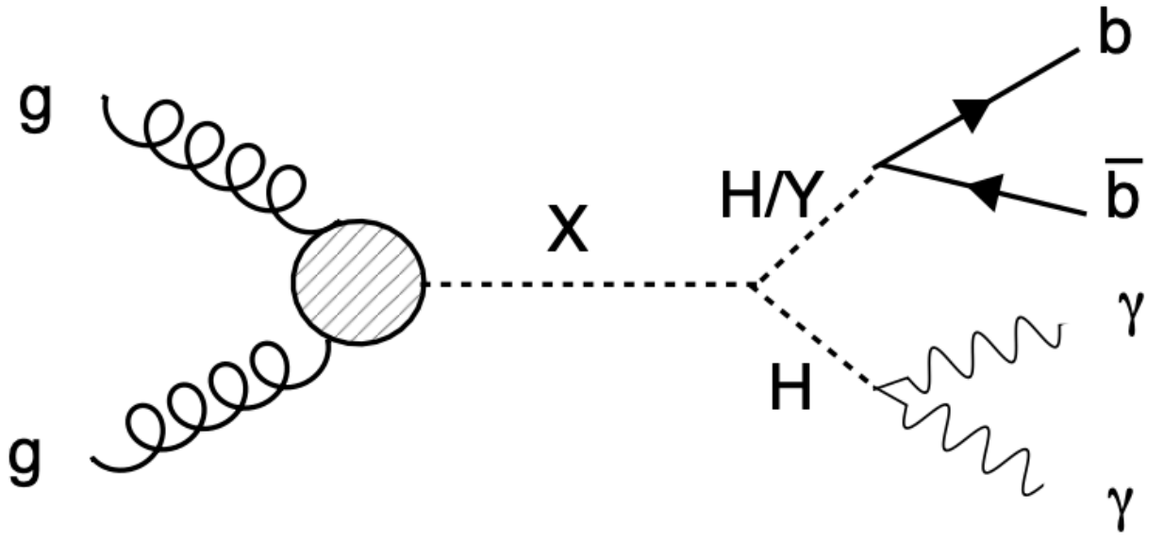
- In this search we consider h→ɣɣ and Y→bb decays

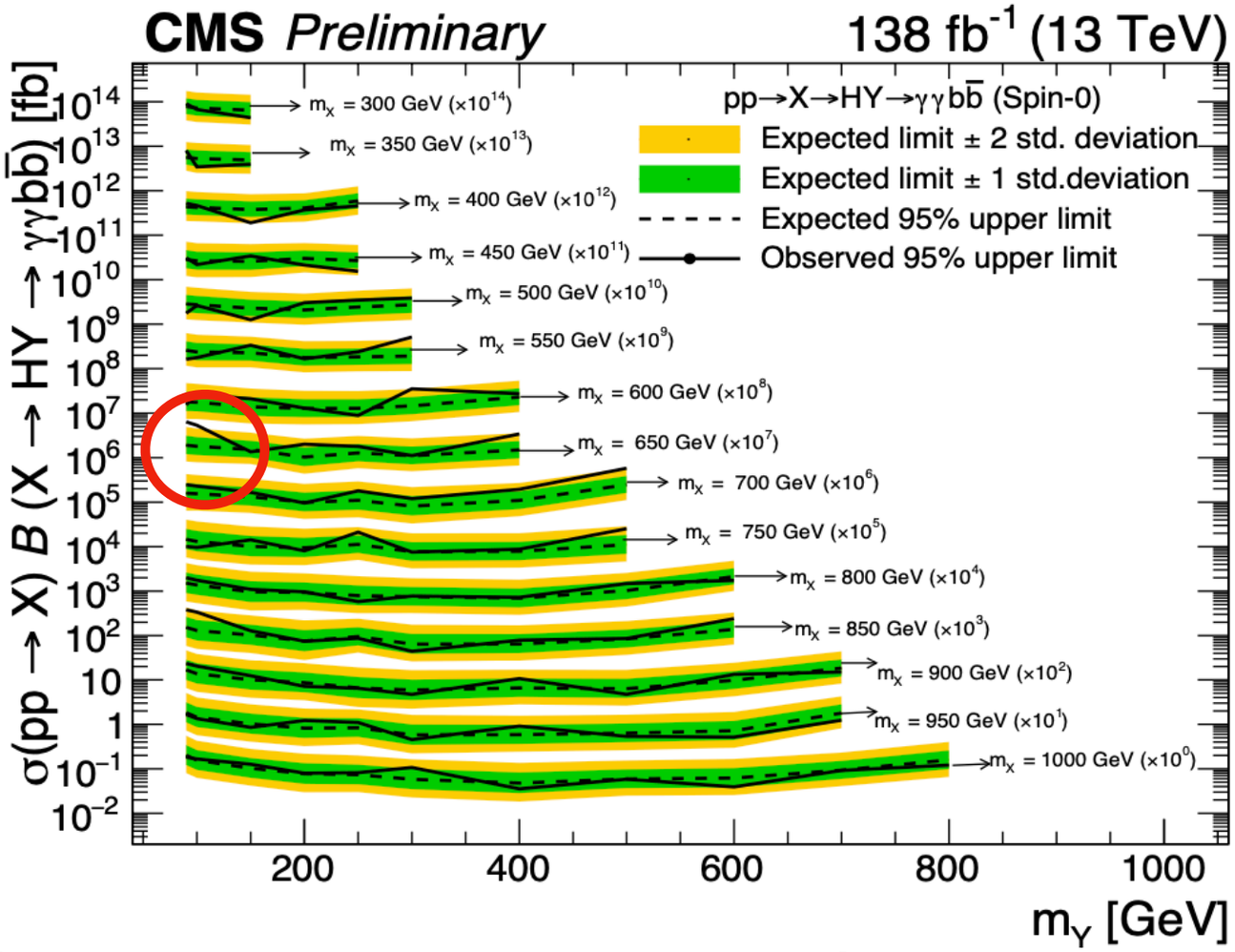
- Largest excess for m_Y=90 GeV,
  m_X = 650 GeV

  - Local (global) significance of 3.8 (2.8)σ @ m_Y=90 GeV

  - Note global significance only accounts for the $m_Y < 150$ GeV search range

  - Local significance of 3.5σ @ m_Y=100 GeV



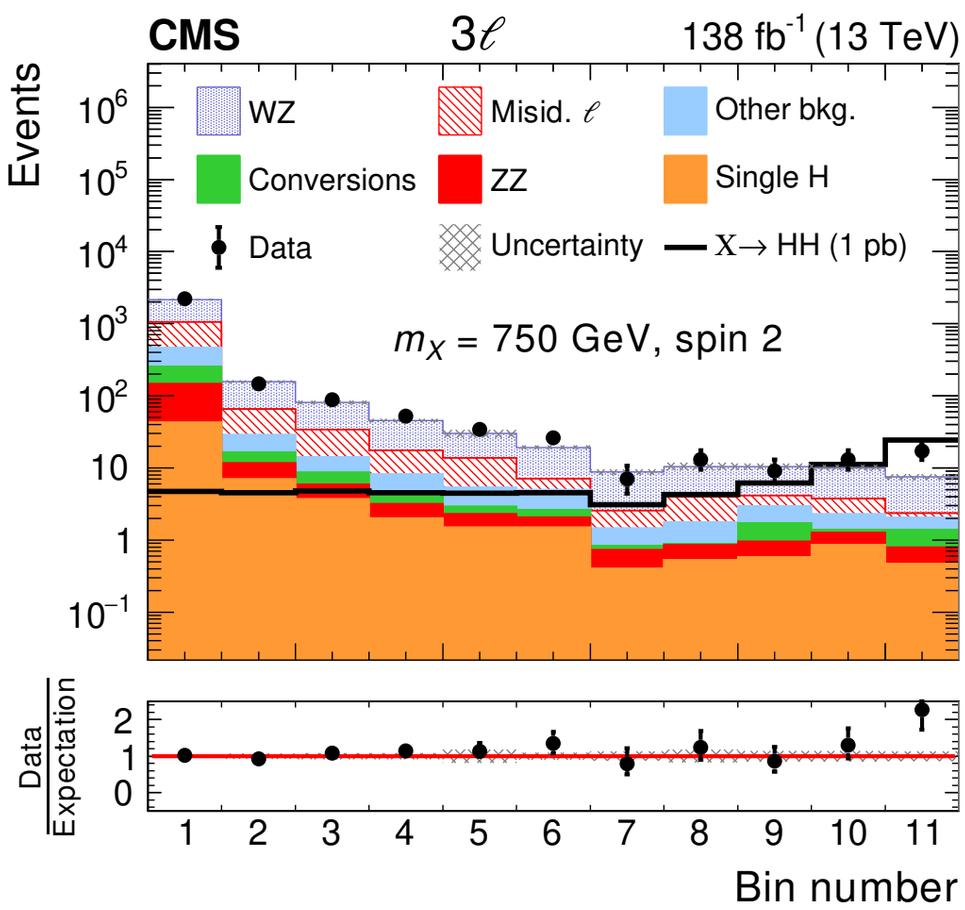


HIG-21-011

(Results in bbbb (boosted) and bb$\tau\tau$ final state in backup)

H→hh→multilepton

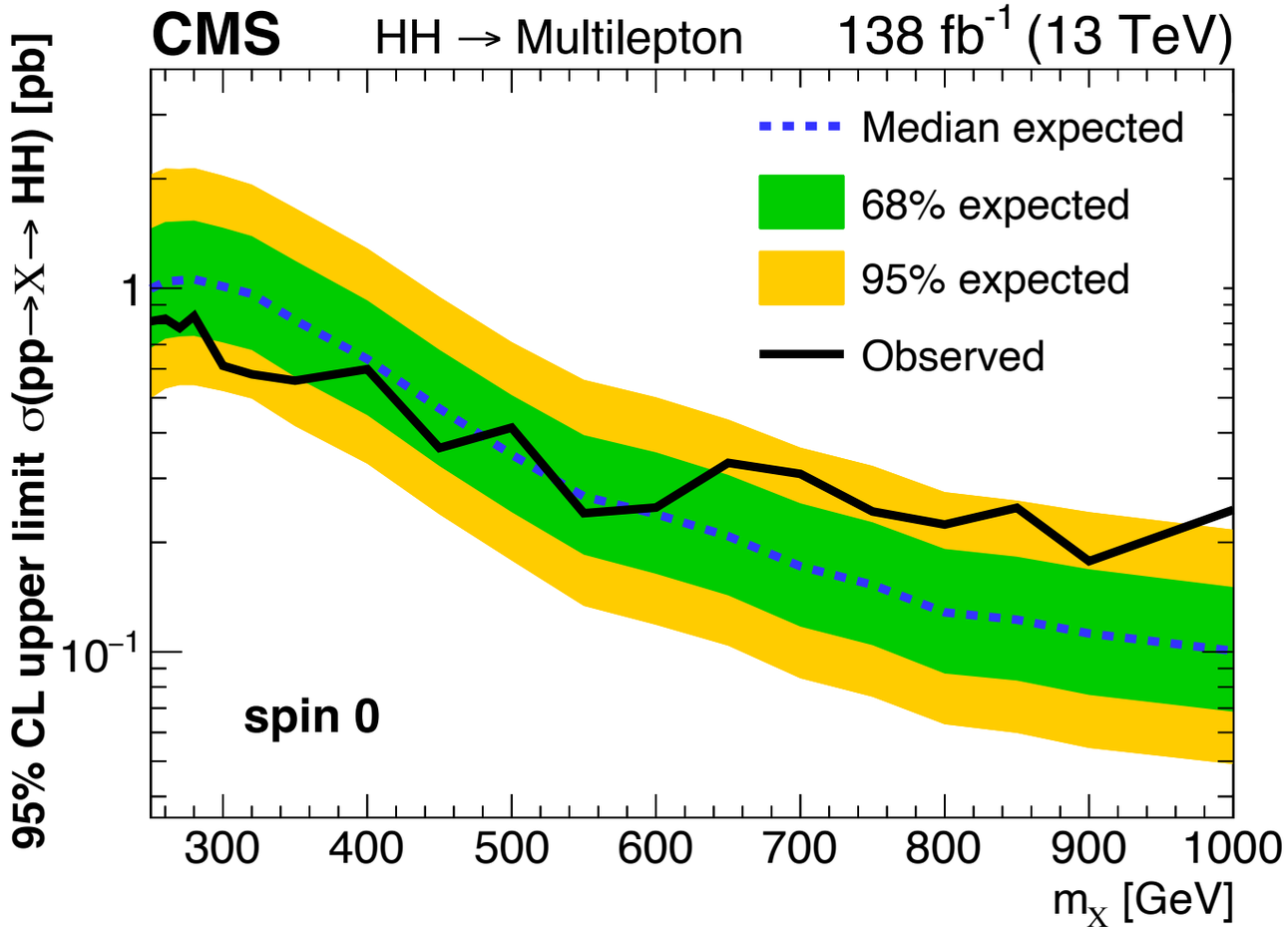
- H→hh typically split by h final state
  - Different final states can probe different H mass regions (branching-ratios vs signal purity)
- Most recent new result by CMS considers “multilepton” final state
  - This covers h→WW / $\tau\tau$ decays
- Split events into channels depending on number of light leptons and τ_h in final state
- BDT to separate signal and background
  - Fit output score to extract results



HIG-21-002

H→hh→multilepton

- Overall the data consistent with background-only hypothesis
- Limits set of cross-section for spin 0 and spin 2 hypotheses

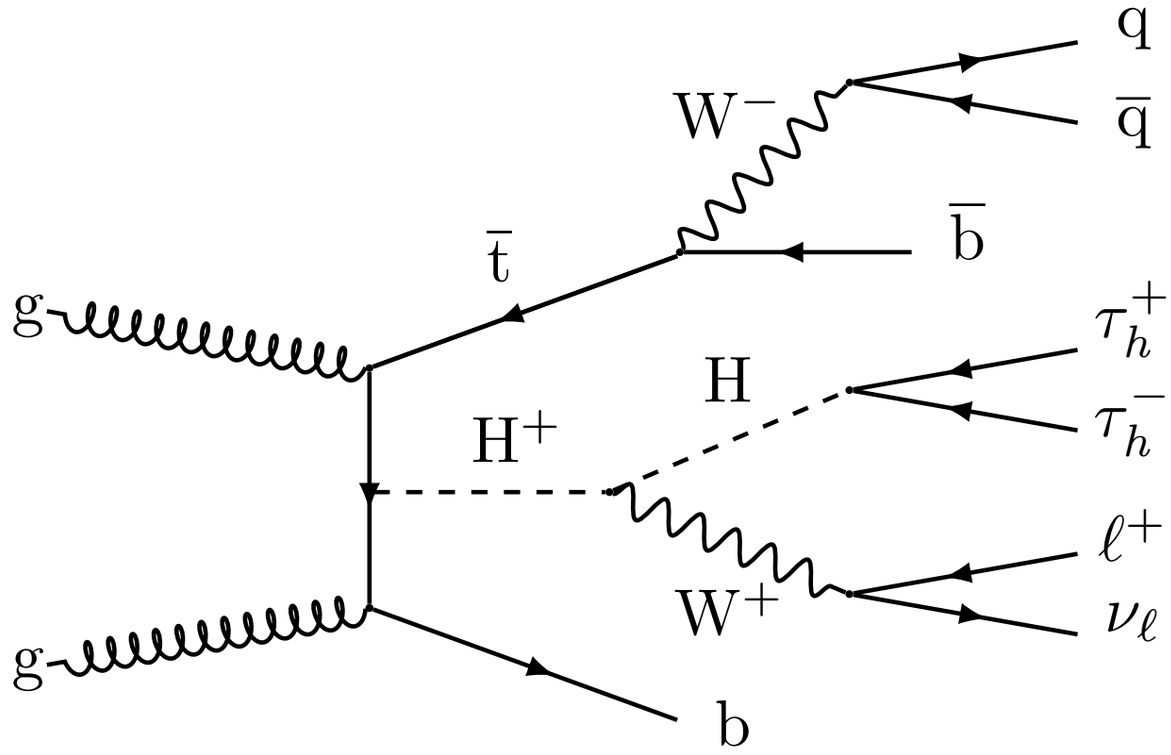


HIG-21-002

Charged Higgs

$H^{\pm} \rightarrow WH$, $H \rightarrow \tau\tau$

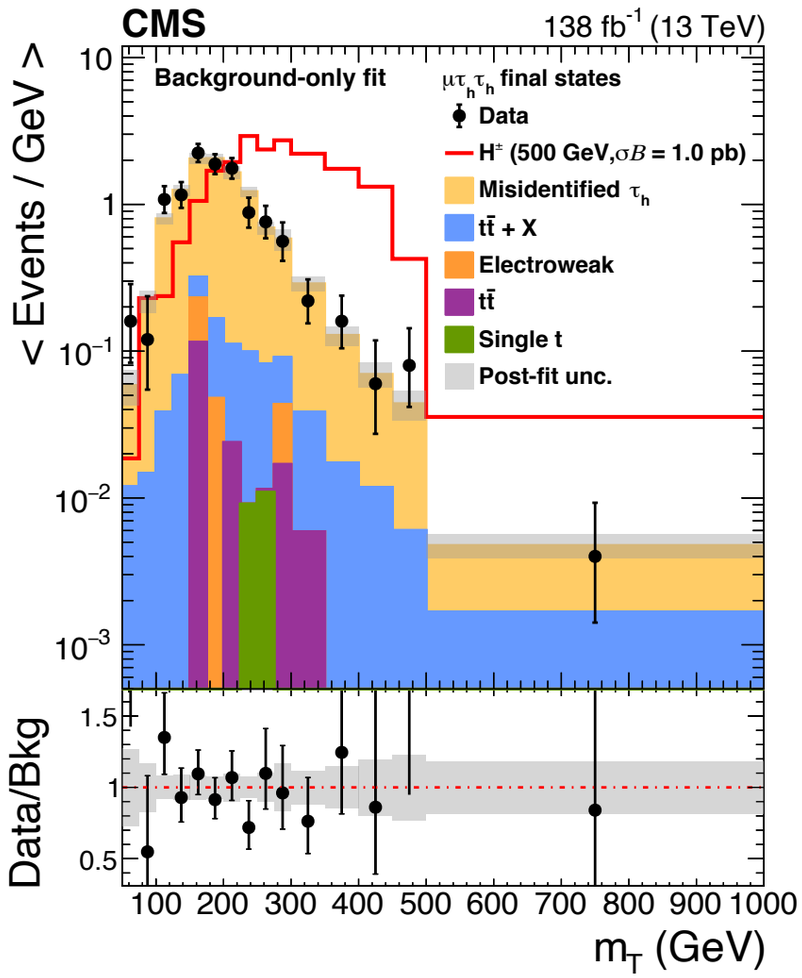
- Search for $H^{\pm}$ decaying into WH (m_H=200 GeV)
- Produced in association with top quark
  - Tag hadronic top decays identified using resolved top quark tagger based on neural network (NN)
- H reconstructed in $\tau\tau$ final state
  - $\tau\tau$ decays into $\tau_h\tau_h$, $\mu\tau_h$, or $e\tau_h$ pairs
- May also get additional lepton from W
  - Split into 4 most sensitive channels: $\mu\tau_h\tau_h$, $e\tau_h\tau_h$, $\mu\tau_h$, $e\tau_h$

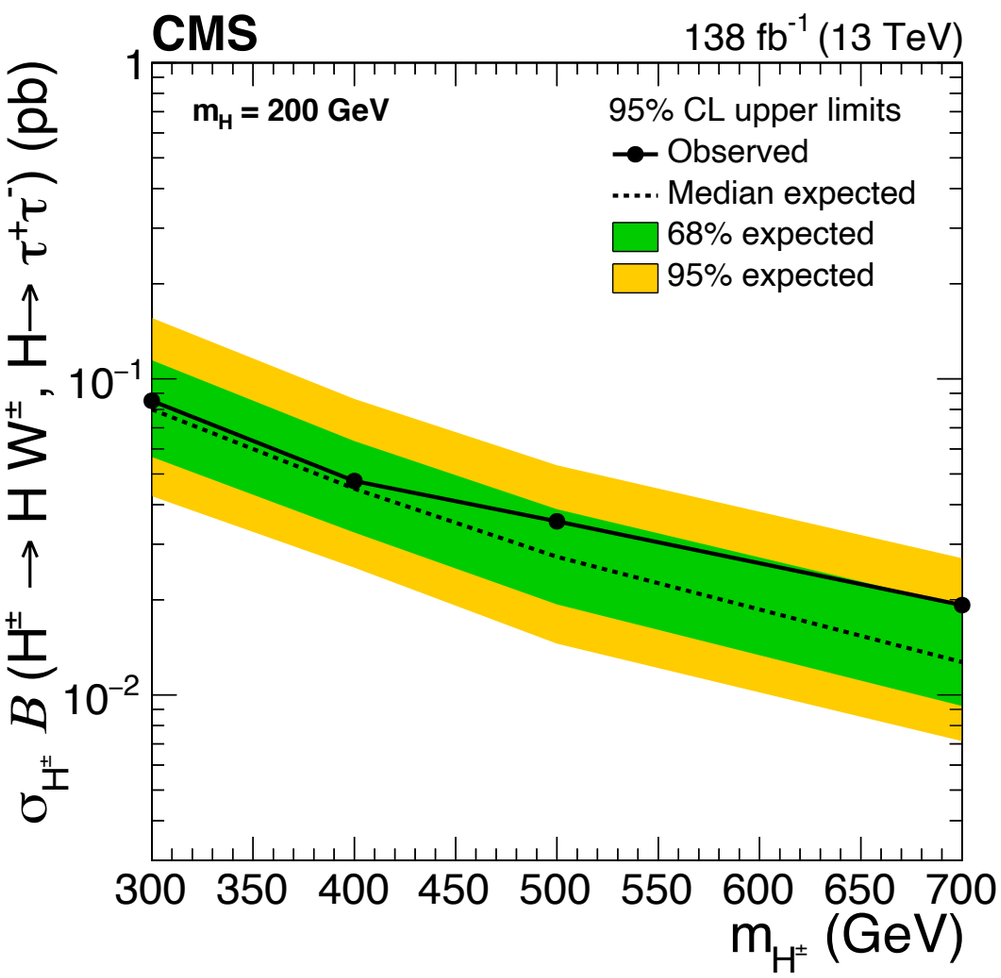


HIG-21-010

$H^{\pm} \rightarrow WH, H \rightarrow \tau\tau$: Results

- Discriminating variables:
  - $l\tau_h\tau_h$ channels: transverse mass of $H^{\pm}$ (m_T)
  - $l\tau_h$ channels: BDT based discriminant
- No statistically significant excess observed - set limits on cross-section vs $m_{H^{\pm}}$





HIG-21-010

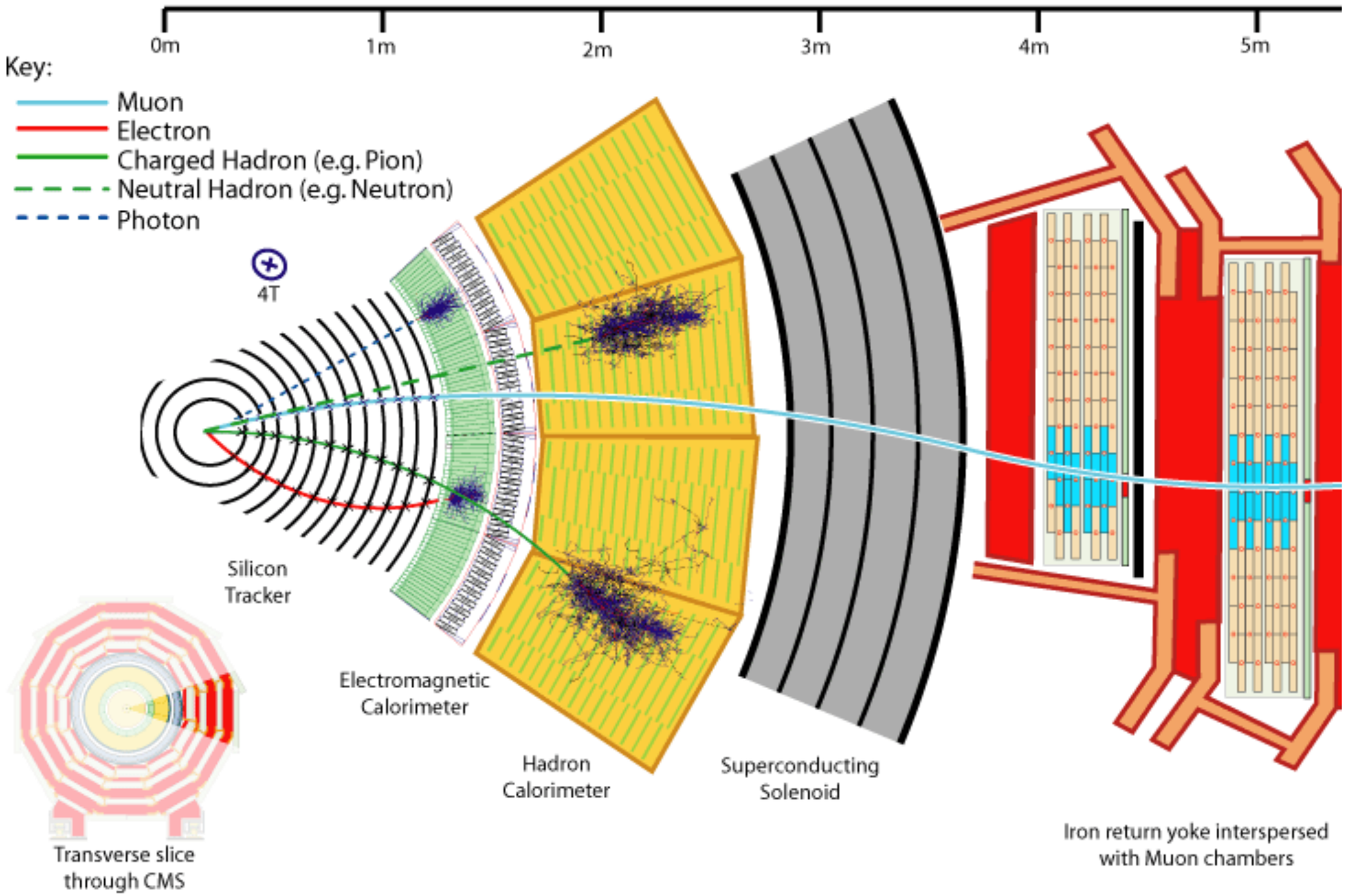
Summary

- Presented the latest results from the CMS experiment in searches for extended Higgs sectors
- No conclusive signals observed yet, but a few interesting excesses!
- Several analyses using the Run 2 dataset expected in the near future
- Additionally Run 3 has begun, expect updates in the next few years

Thanks for your attention!

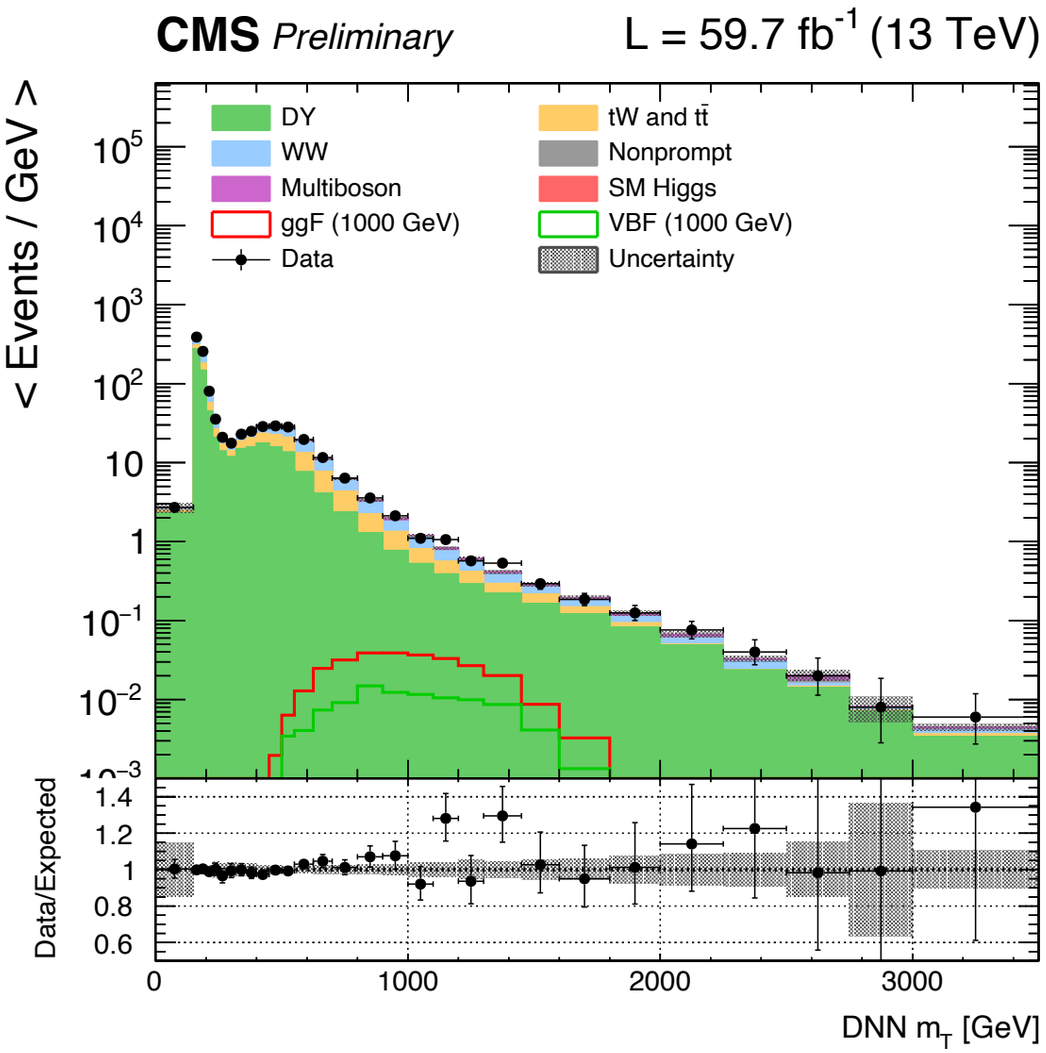
Backup

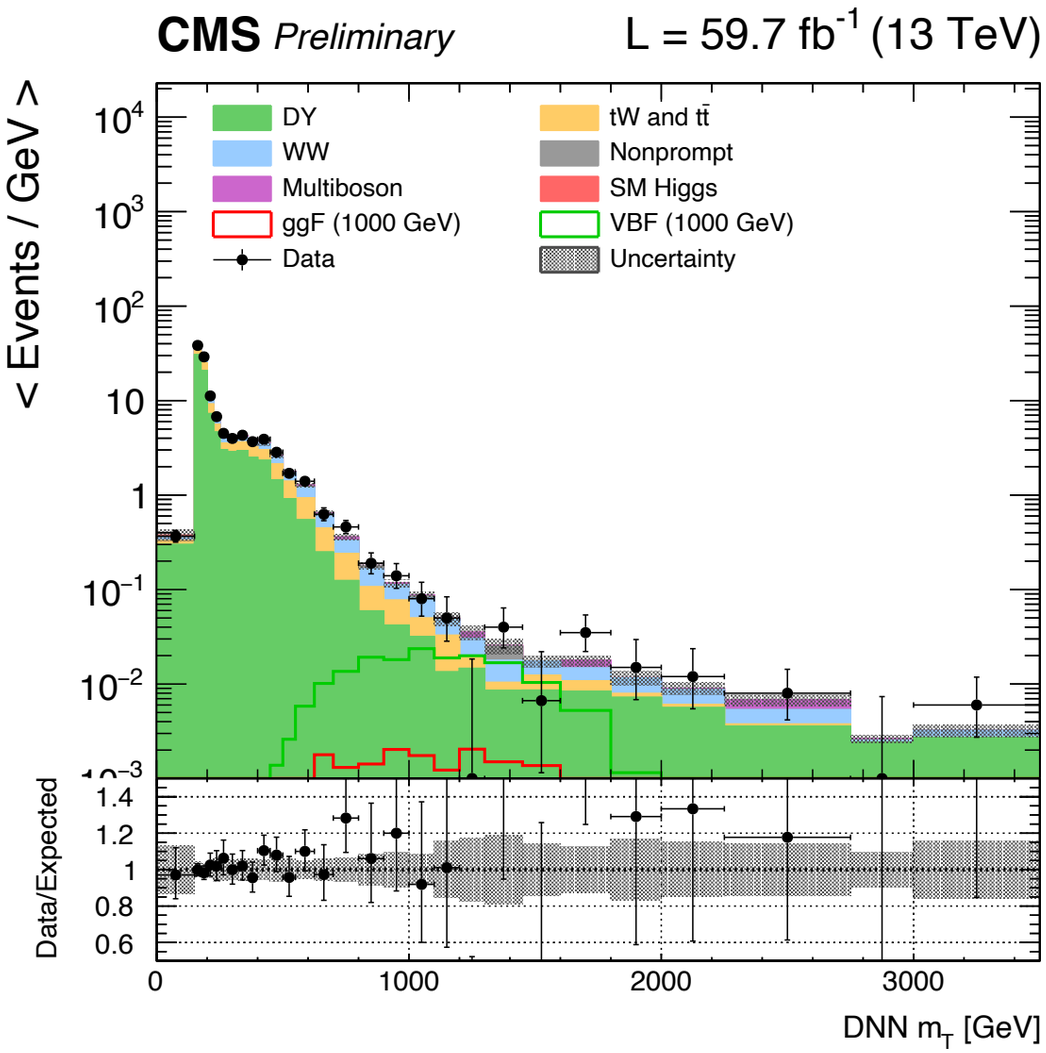
The CMS detector



H→WW: Other fitted distributions

- Additional examples of fitted distribution for H→WW search in the μμ final state

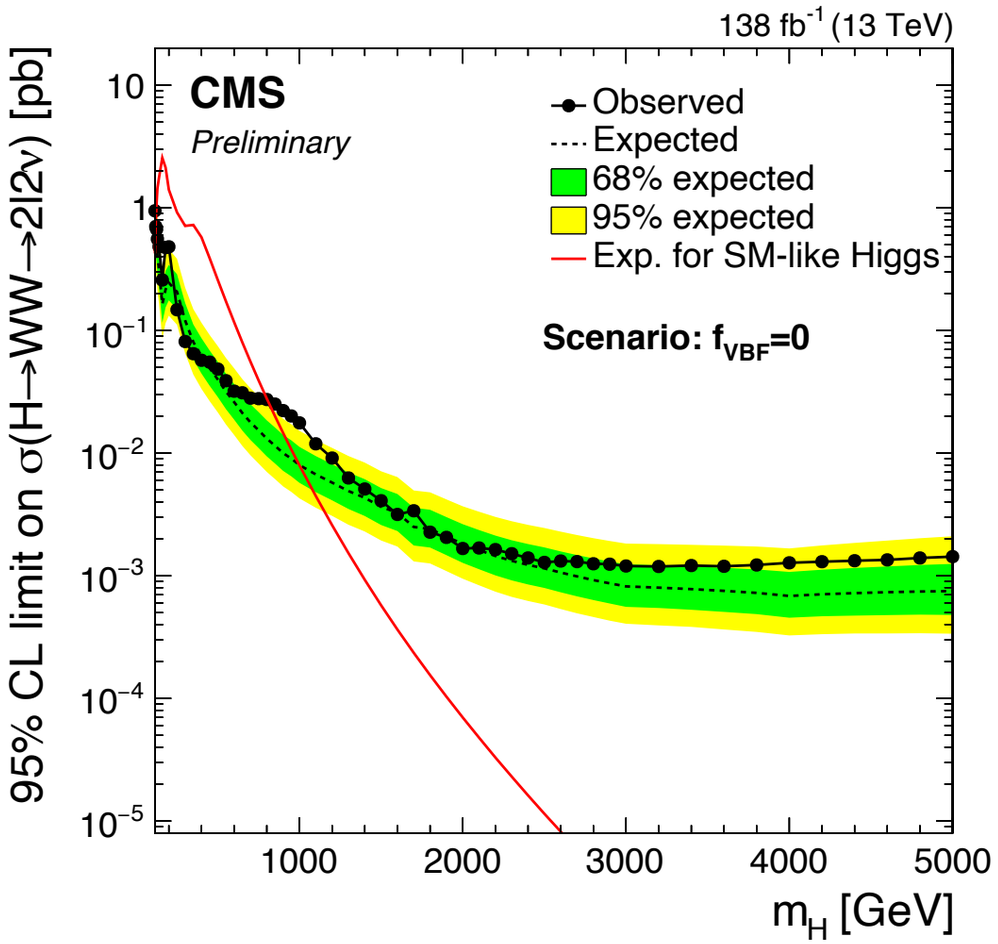


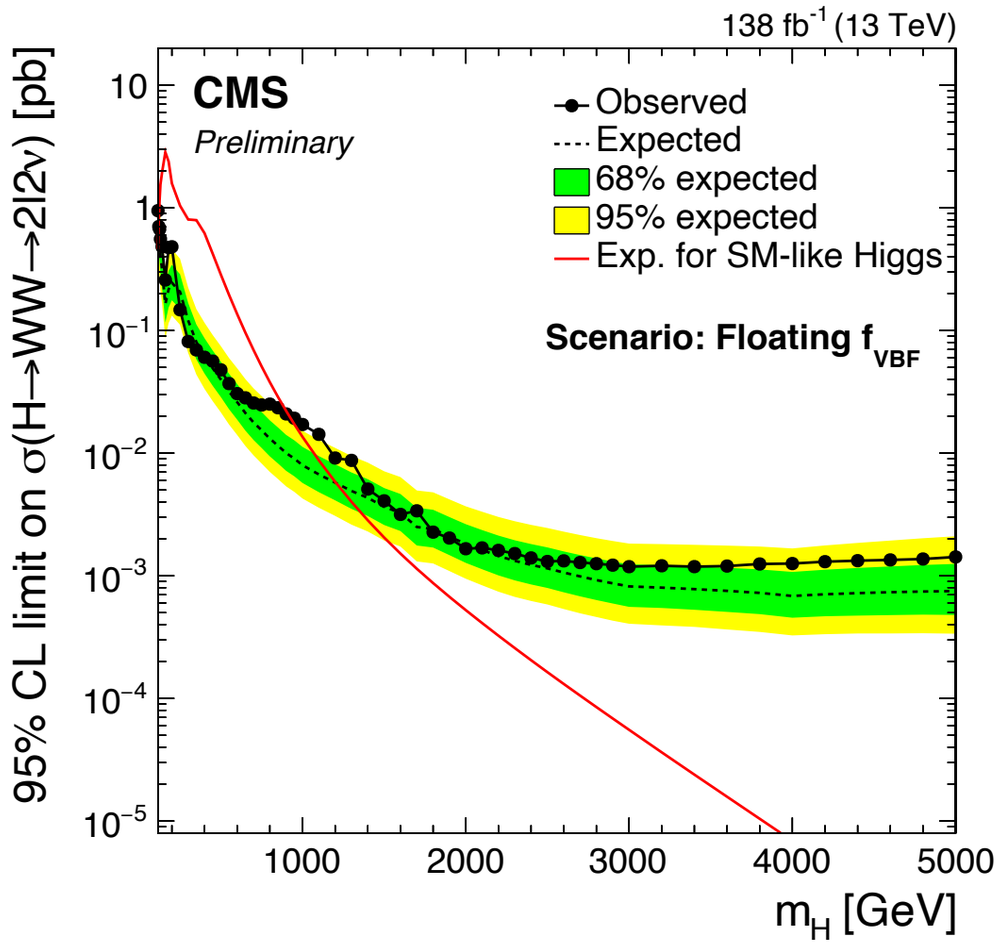


HIG-20-016

H→WW: Other VBF assumption

- Additional examples of H→WW limits for ggϕ-only (left) and VBF-only (right) scenarios





HIG-20-016

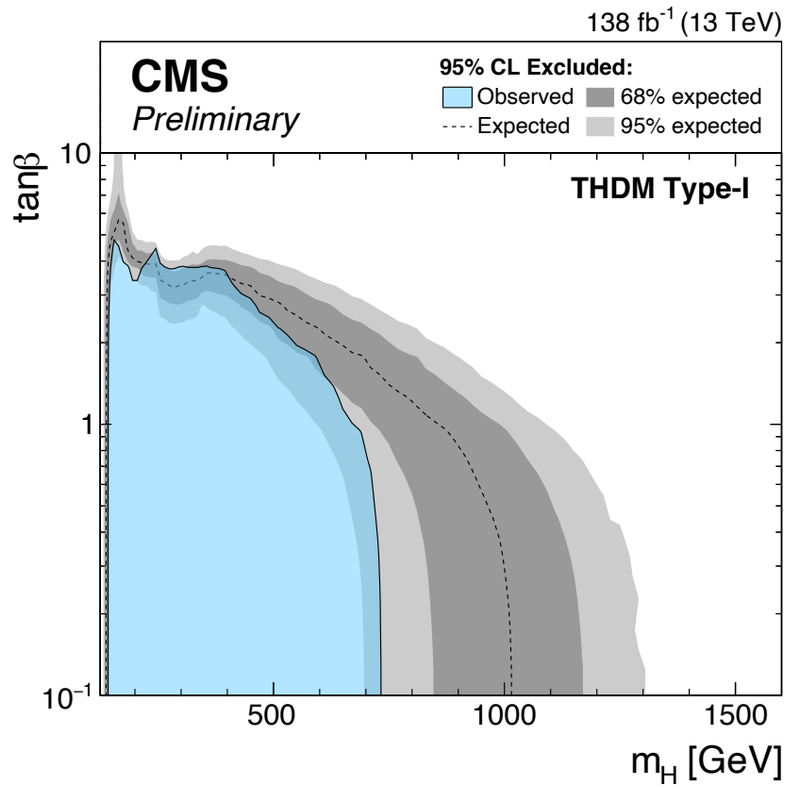
H→WW: DNN

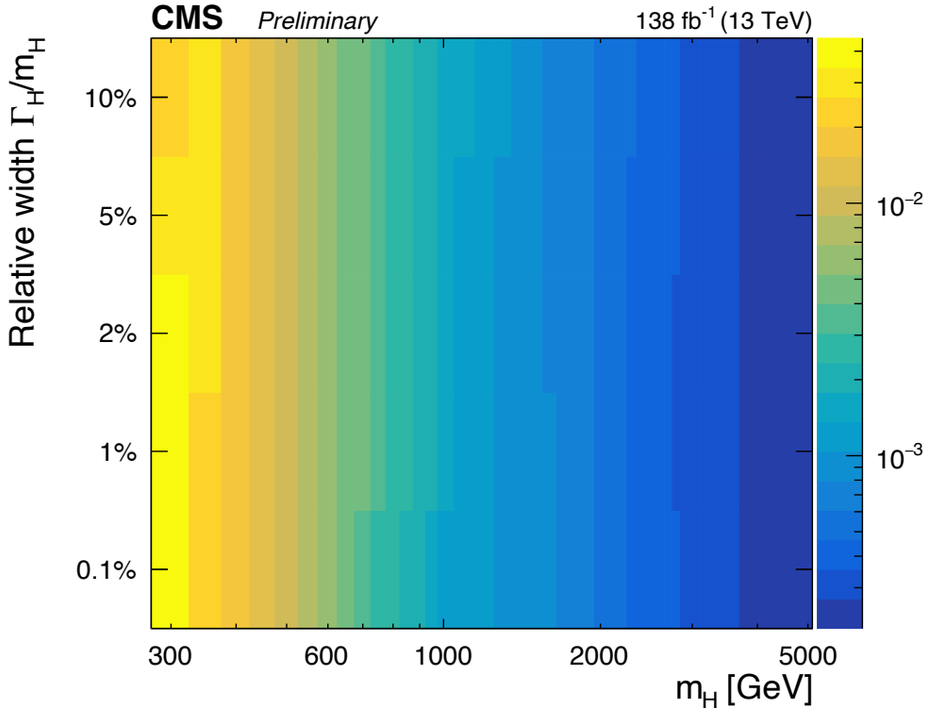
- Multiclass DNN separates VBF ggϕ signal and backgrounds
- Trained on all signal mass hypotheses combined
- x,y, and z components of two leading leptons momenta
- x,y, and z components of four leading jets momenta, and their masses
- Djet mass and pseudorapidity separation for combinations of 4 leading jets
- Jet multiplicity
- x and y components of missing momentum
- H mass, di-lepton mass and di-lepton p_T
- Scalar H_T sum of jets, leptons, and MET
- Several transverse mass quantities of leptons and MET
- Angular correlation between leptons, and between leptons and MET

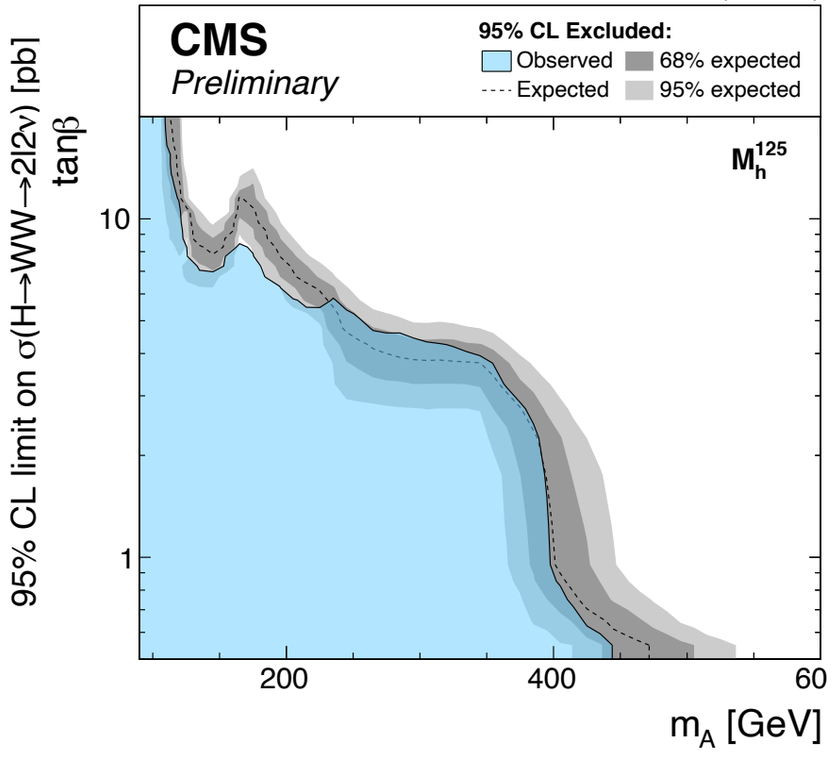
HIG-20-016

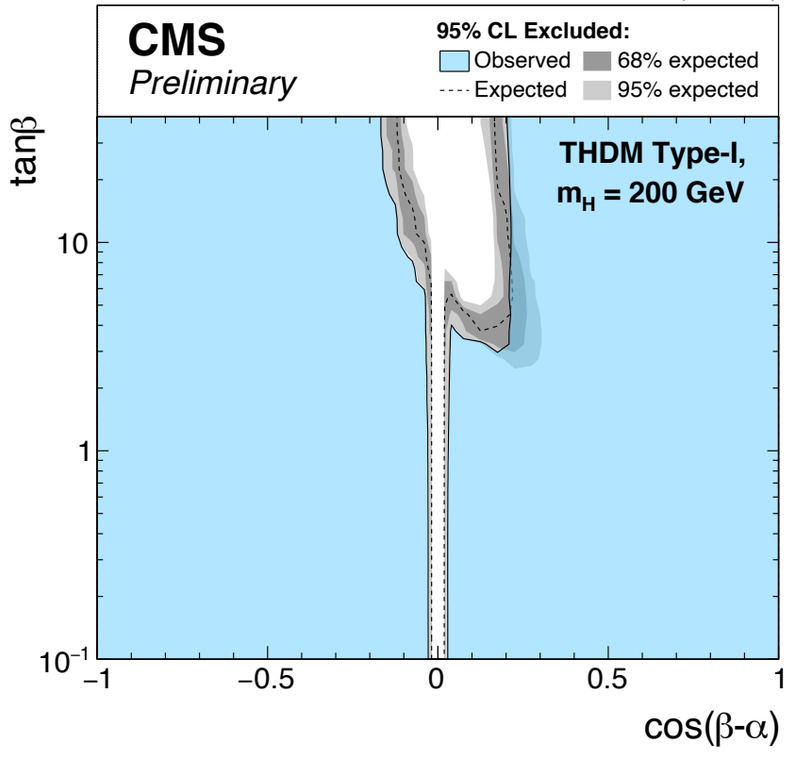
H→WW: Other interpretations

- Left: limits set for different width hypotheses
- Middle Limits set in alternative MSSM benchmark
- Limits set in 2HDM in tanβ vs cos(β-α) plane









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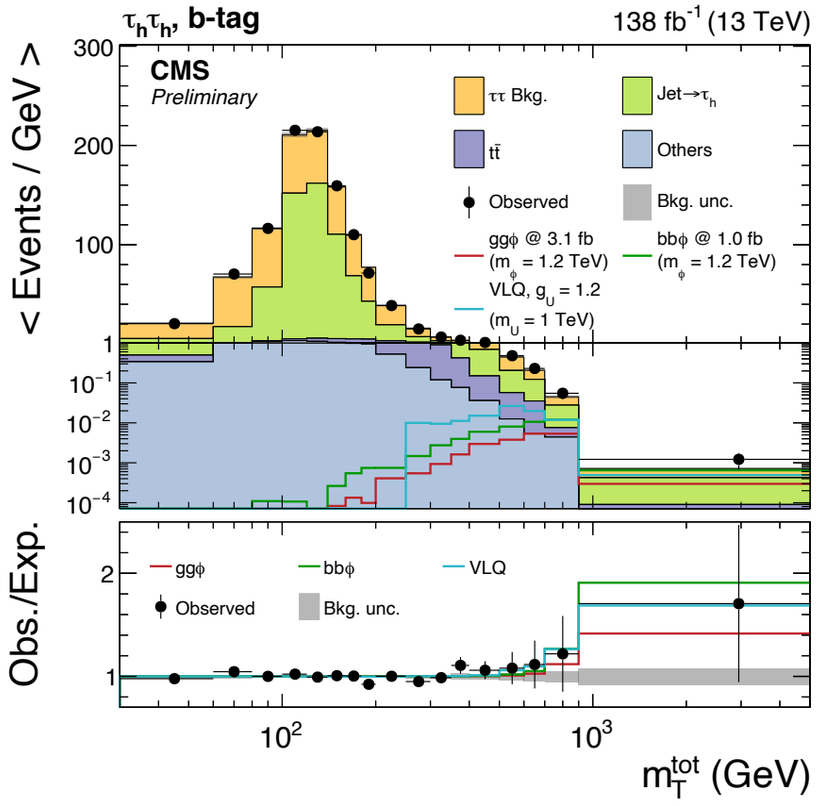
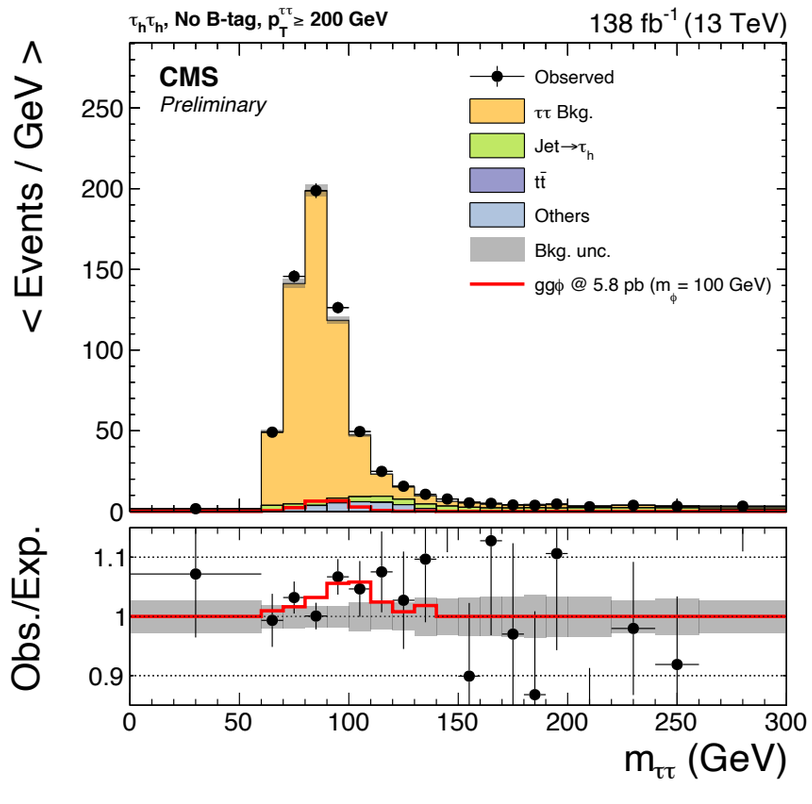
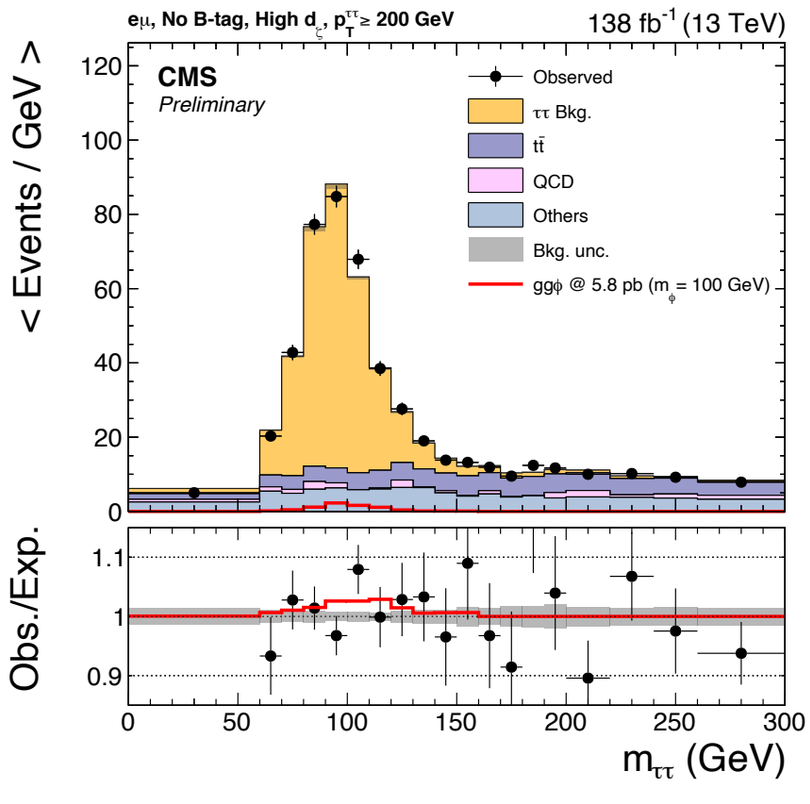
H/A→$\tau\tau$: Other fitted distributions

- Additional examples of fitted distribution for H/A→$\tau\tau$ searches







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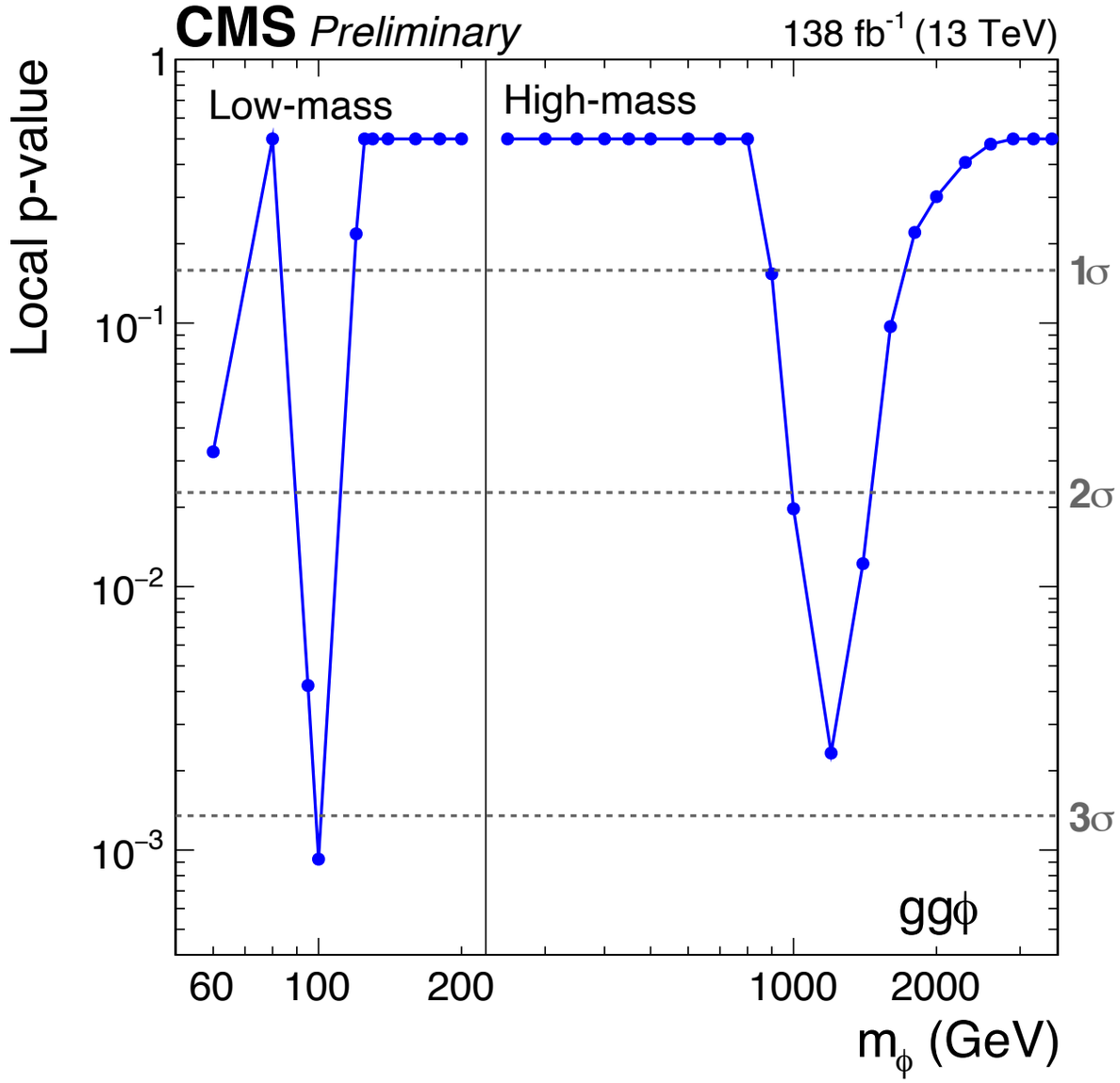
H/A→$\tau\tau$: Significances

- Significances as a function of mass



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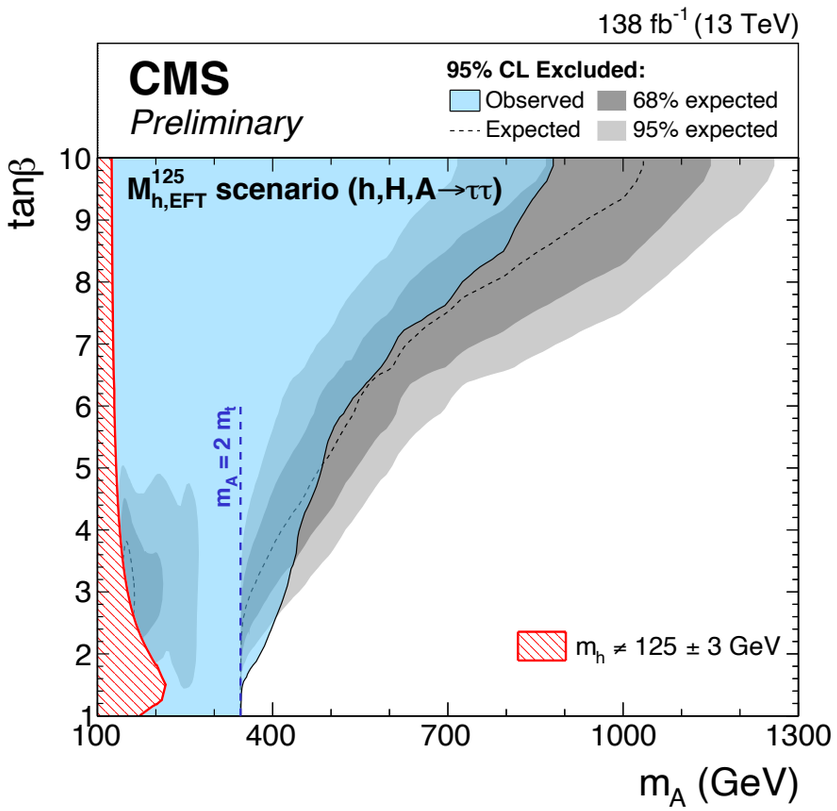
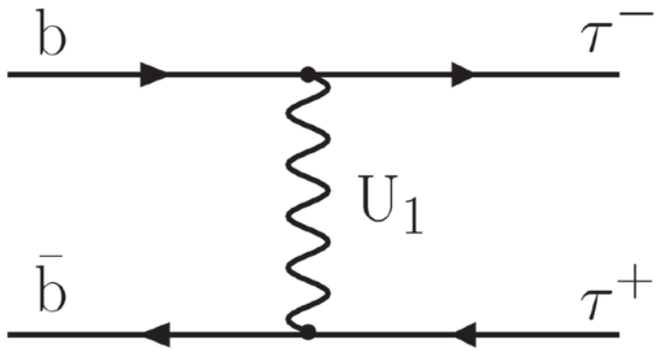
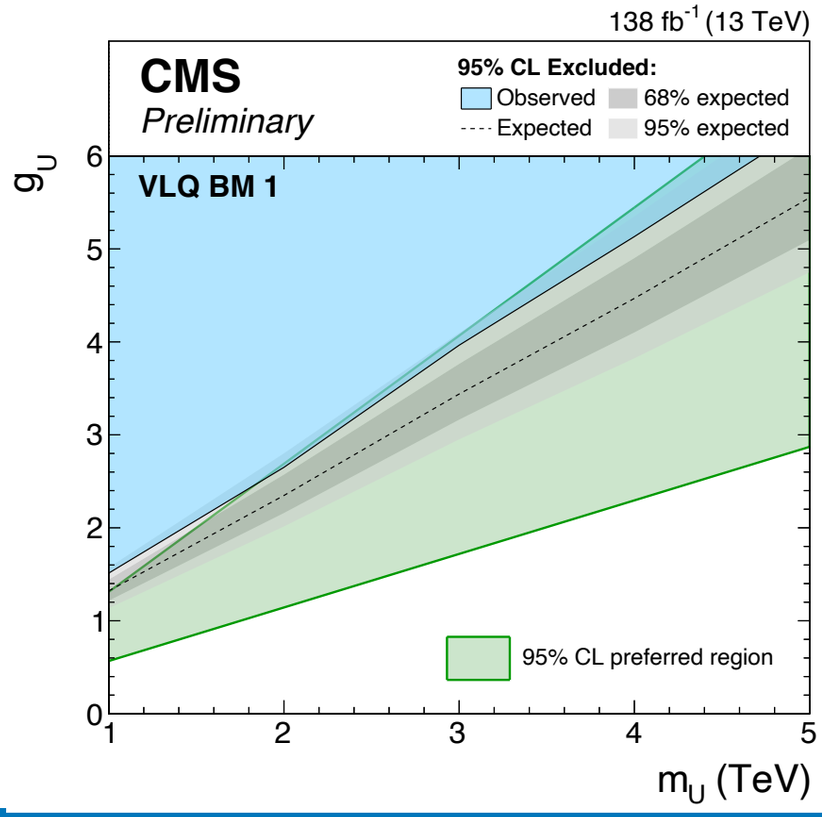
H/A→$\tau\tau$: Other interpretations

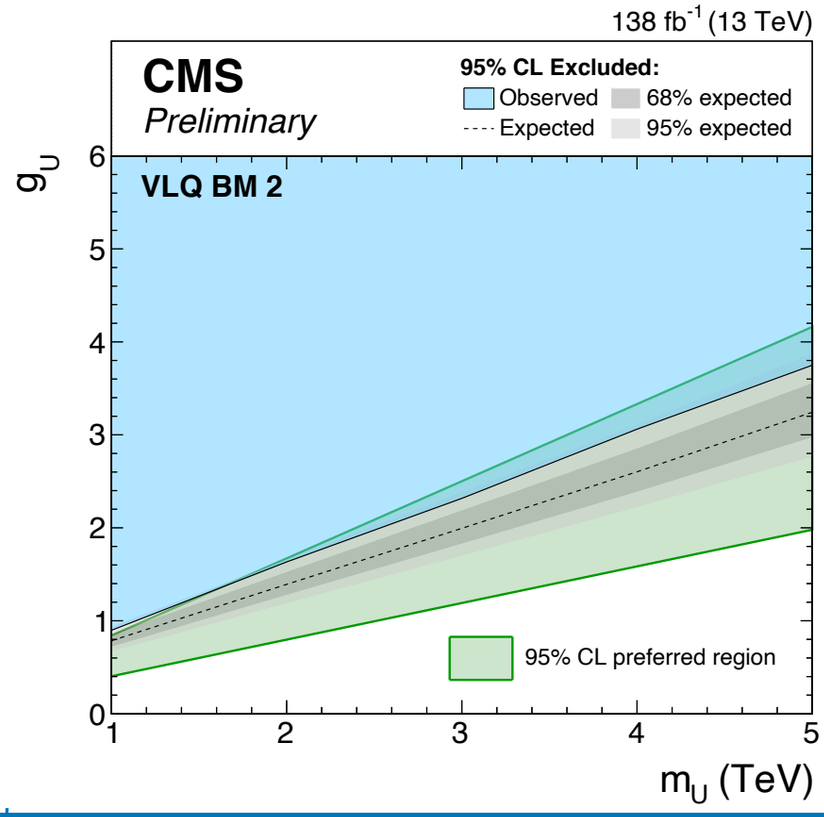
- Additional MSSM benchmark scenario considered

- Also interest results in models with vector-leptoquark (t-channel exchange)







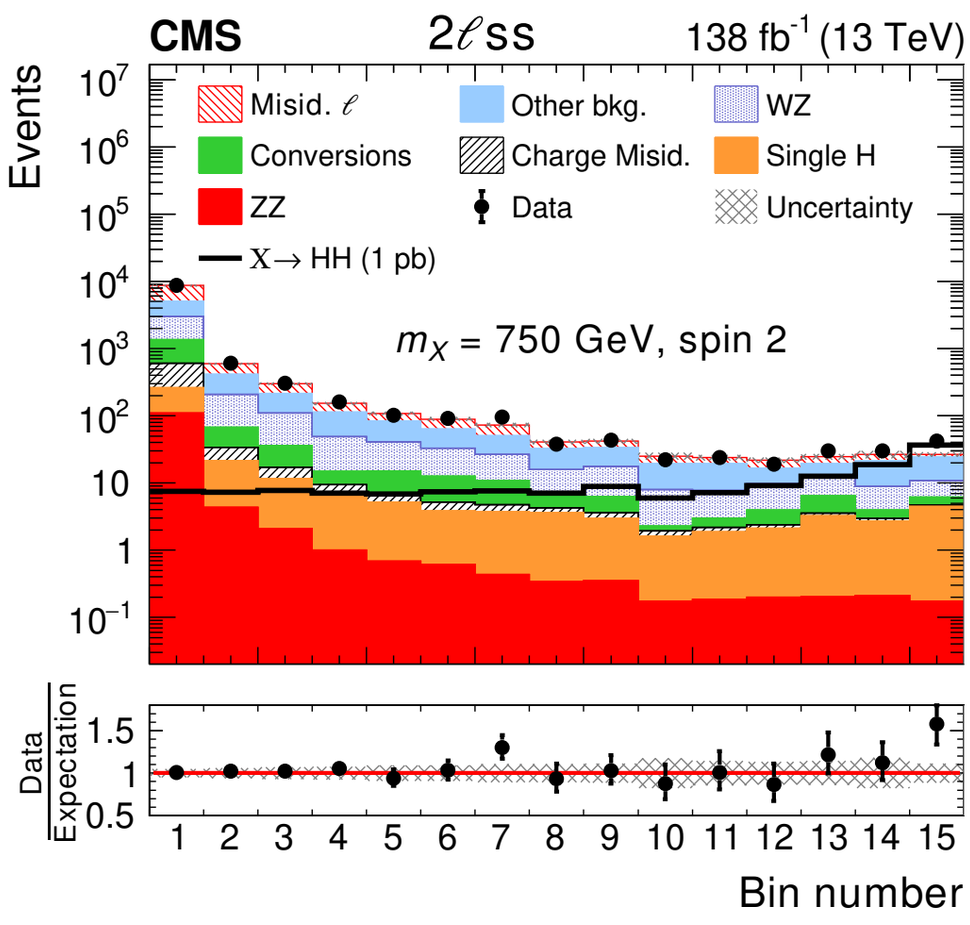


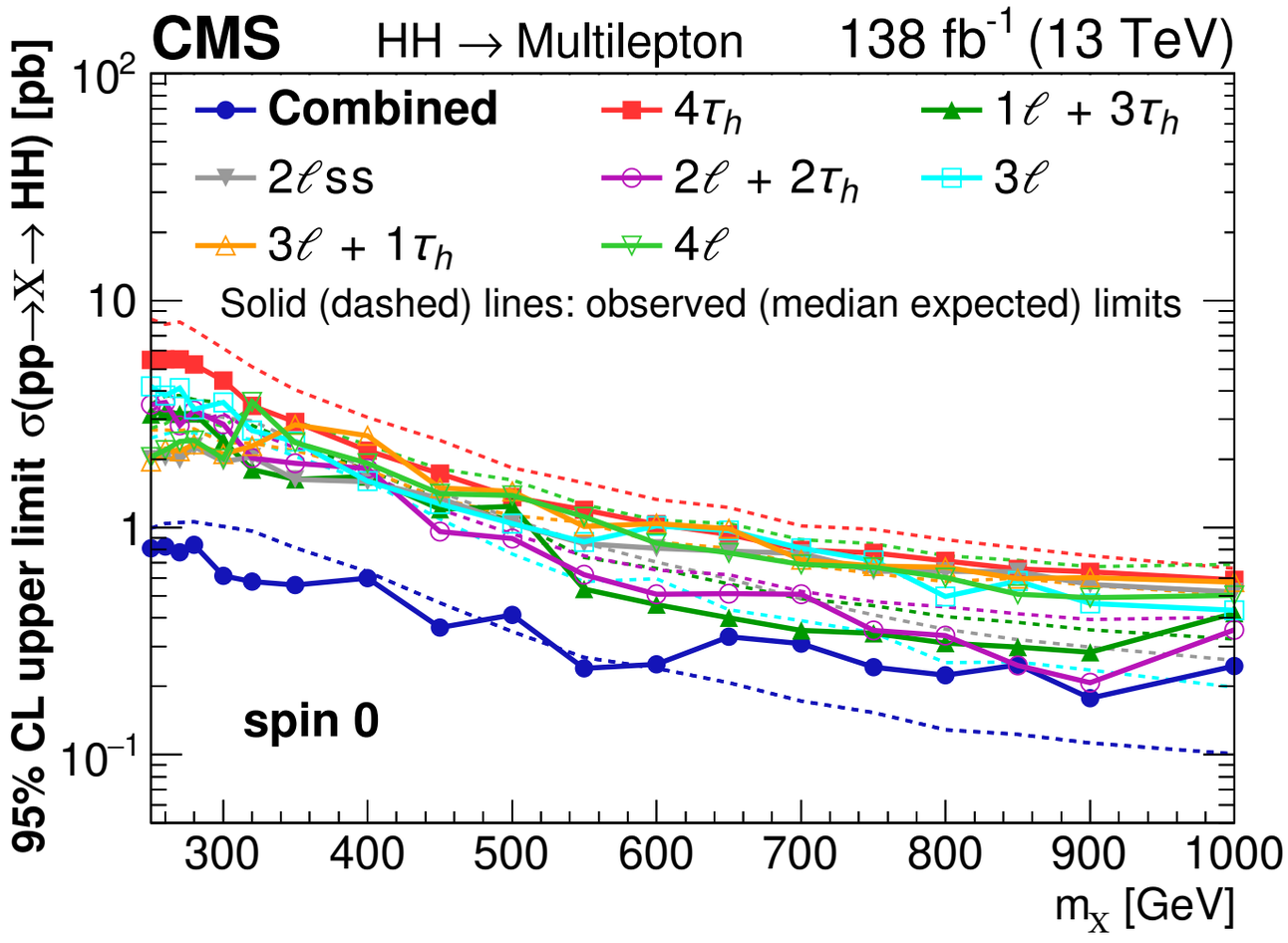
HIG-21-001

H→hh→multilepton

- H→hh→multilepton analysis left plot shows discriminating variable for 2lss category

- Also show limits split by channels (right) for spin 0 resonance

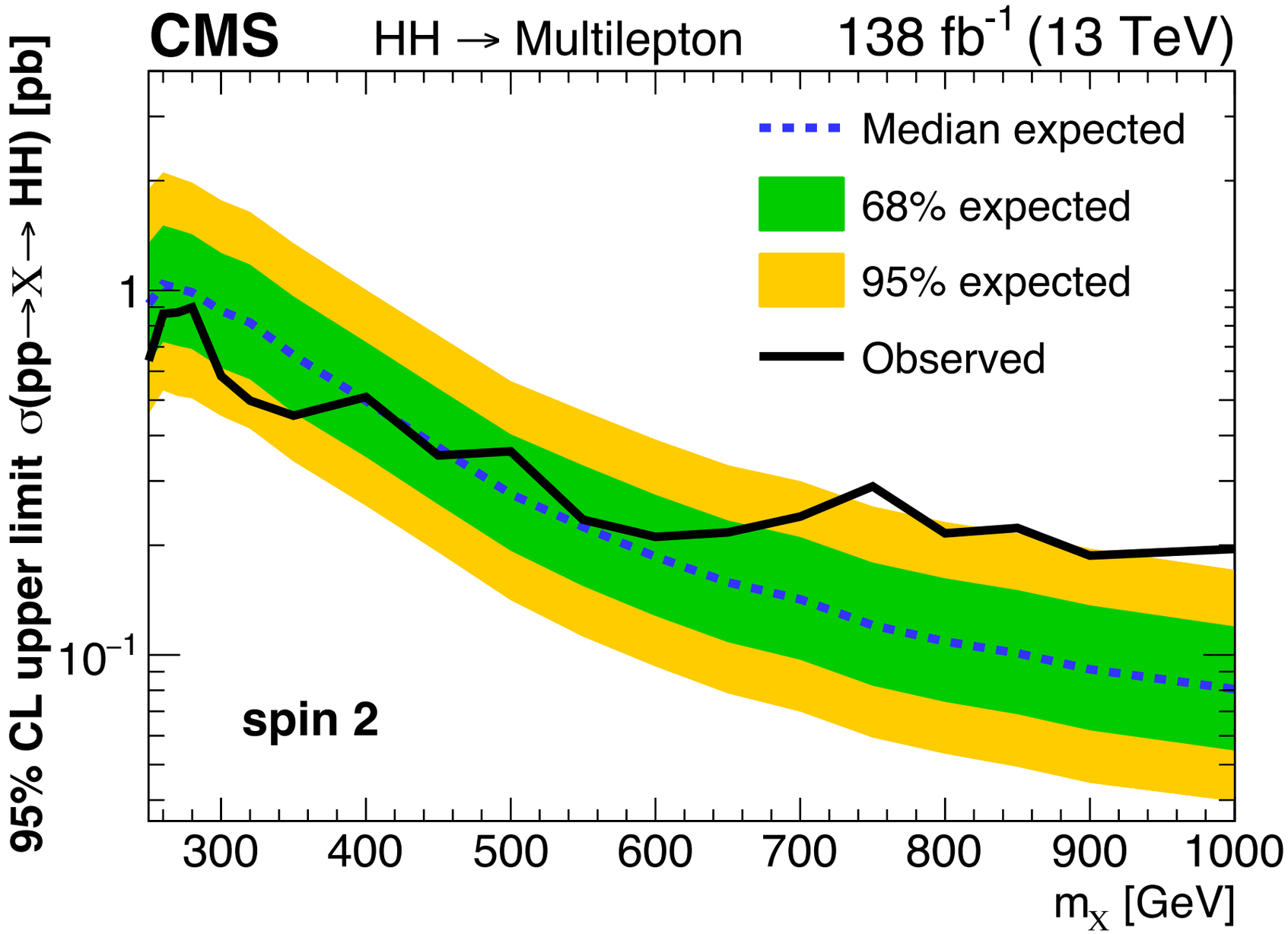




HIG-21-002

H→hh→multilepton: spin 2

- Limits for spin 2 resonance



HIG-21-002

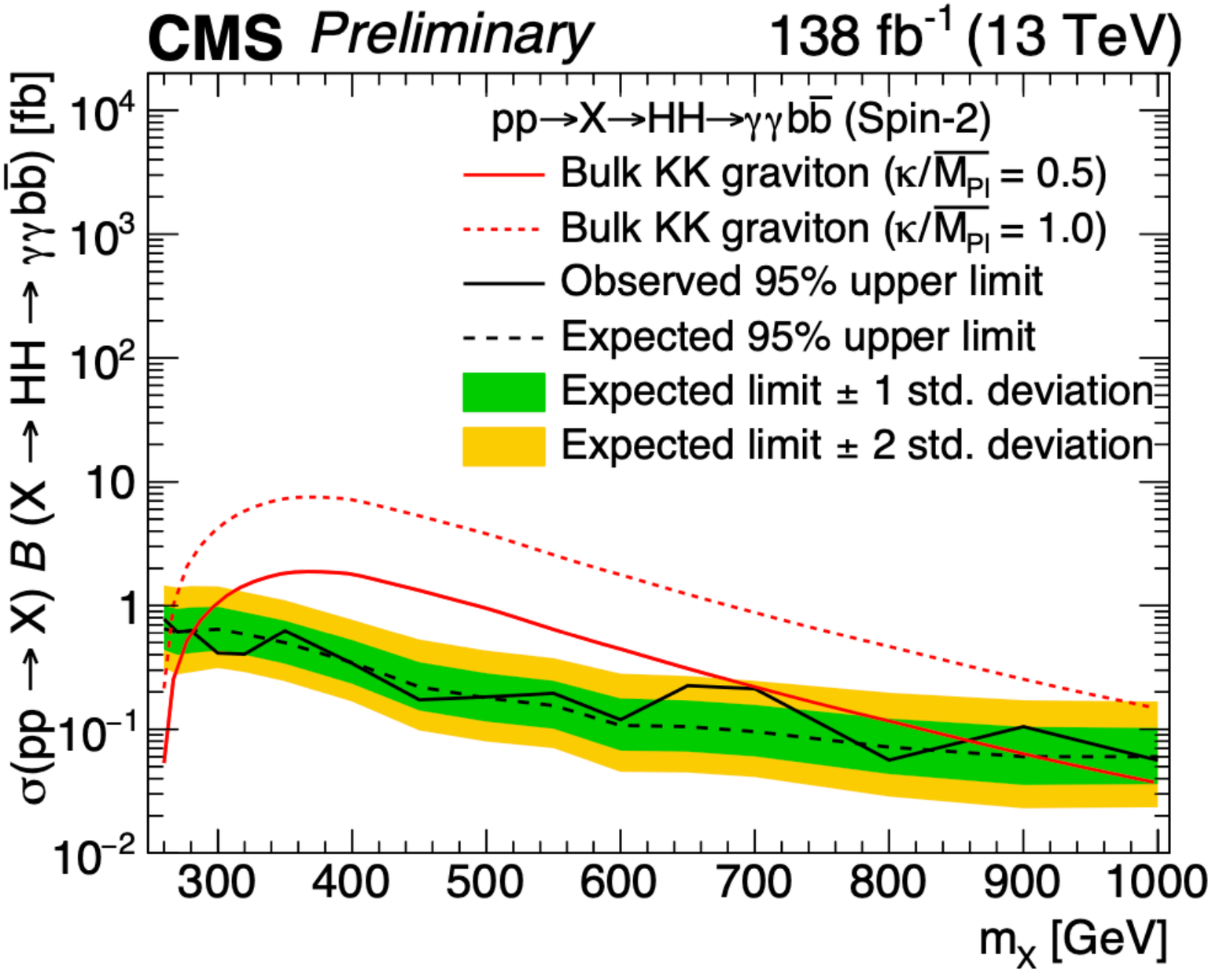
H→hh→multilepton: BDT variables

- BDT variables include:
  - p_T and η of the l and τ_h candidates
  - Angular separation between the l and τ_h
  - Angular separation between the l or τ_h and the nearest jet
  - The jet multiplicity and the missing p_T
  - The scalar p_T sum of the l and τ_h and the jets
  - Mass estimates for the H boson pair
- Trained on all mass MC samples
- Mass is used as a real-values input to the BDT

HIG-21-002

H→hh→bbɣɣ : spin 2

- Limits set for spin 2 hypothesis



HIG-21-011

H→hh(Y)→bbɣɣ: BDT variables

- BDT used to reject non-resonant background. Variables include:
- Kinematic variables:
  - Helicity angles
  - Angular distance between photons and jets
  - p_T/mass for photons and jets
- Object ID variables:
  - Leading and subleasing photon ID
  - Leading and subleasing b-jet tagging discriminant
- Resolution variables:
  - Energy resolution of photons and mass resolution of di-photons
  - Energy resolution of jets and mass resolution of di-jets

HIG-21-011

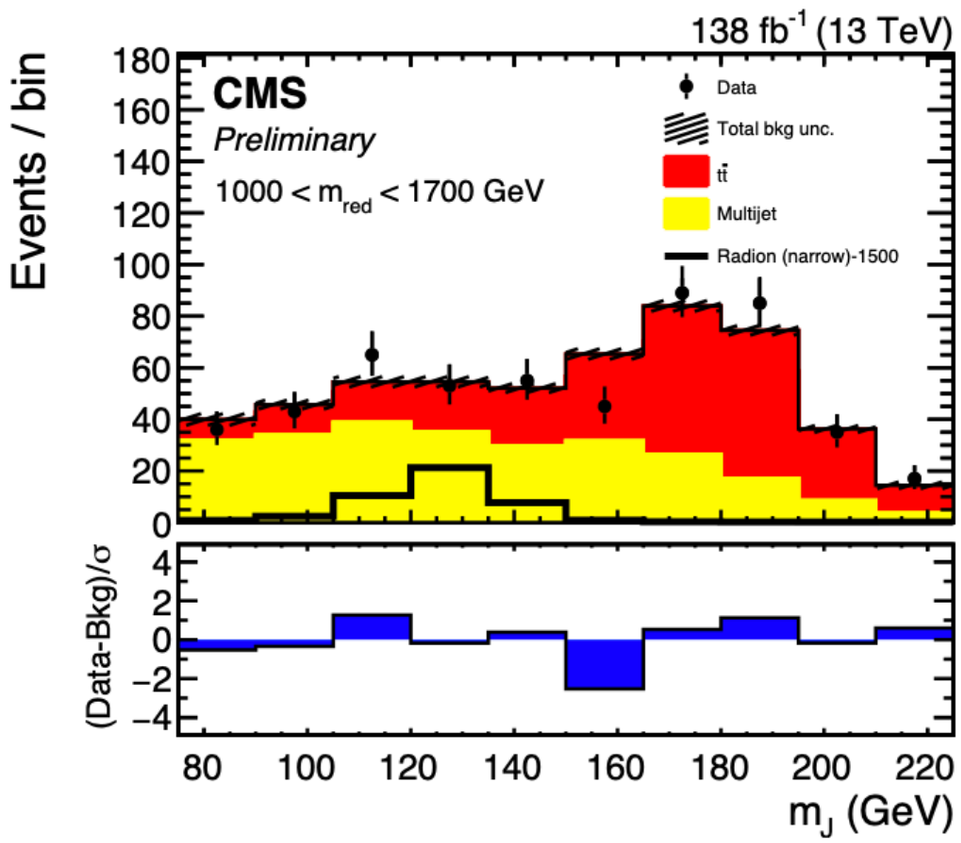
H→hh(Y)→bbɣɣ: 2D fit

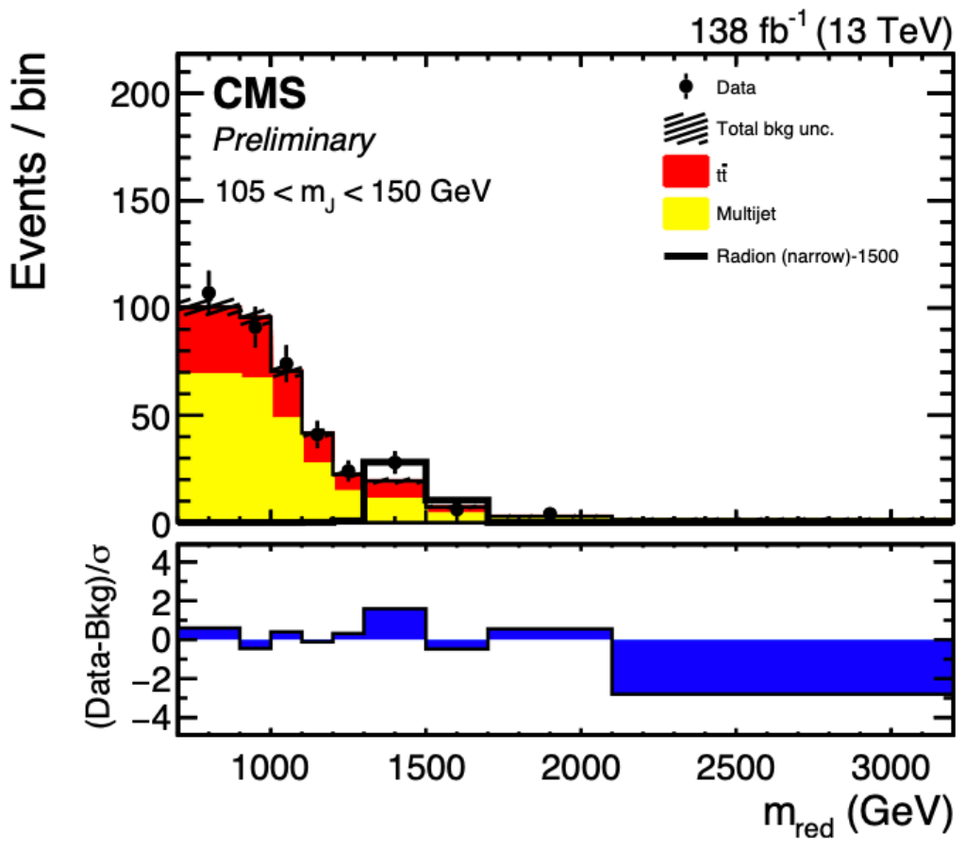
- Results are extracted by performing unbinned maximum likelihood 2D fit of $m_{\gamma\gamma}$ vs m_{jj}
- Signal is modelled by fitting events with a product of two parametric signal models
  - Sum of gaussians for $m_{\gamma\gamma}$ (up to 5 gaussians)
  - A double sided crystal ball (CB) or sum of CB and a Gaussian for m_{jj}
- Correlations between $m_{\gamma\gamma}$ vs m_{jj} found to be negligible from simulations
- For single Higgs background:
  - $m_{\gamma\gamma}$ modelled as before
  - m_{jj} parameterisation depends on production mode e.g for ttH a Gaussian with mean around 120 GeV is used
- Non-resonant background used discrete profiling method is used to fit background $m_{\gamma\gamma}$ and m_{jj} distributions

HIG-21-011

H→hh→bbbb

- Search for boosted bbbb final state
- At last 1 H decay candidate is boosted so 2b's end up in 1 large R jet (AK8)
- DNN based tagger used to select such 2b jets
- Discriminating variables constructed using soft drop masses
- 2D discriminating variable m_J (mass of leading AK8 jet) and "reduced mass" m_{red}

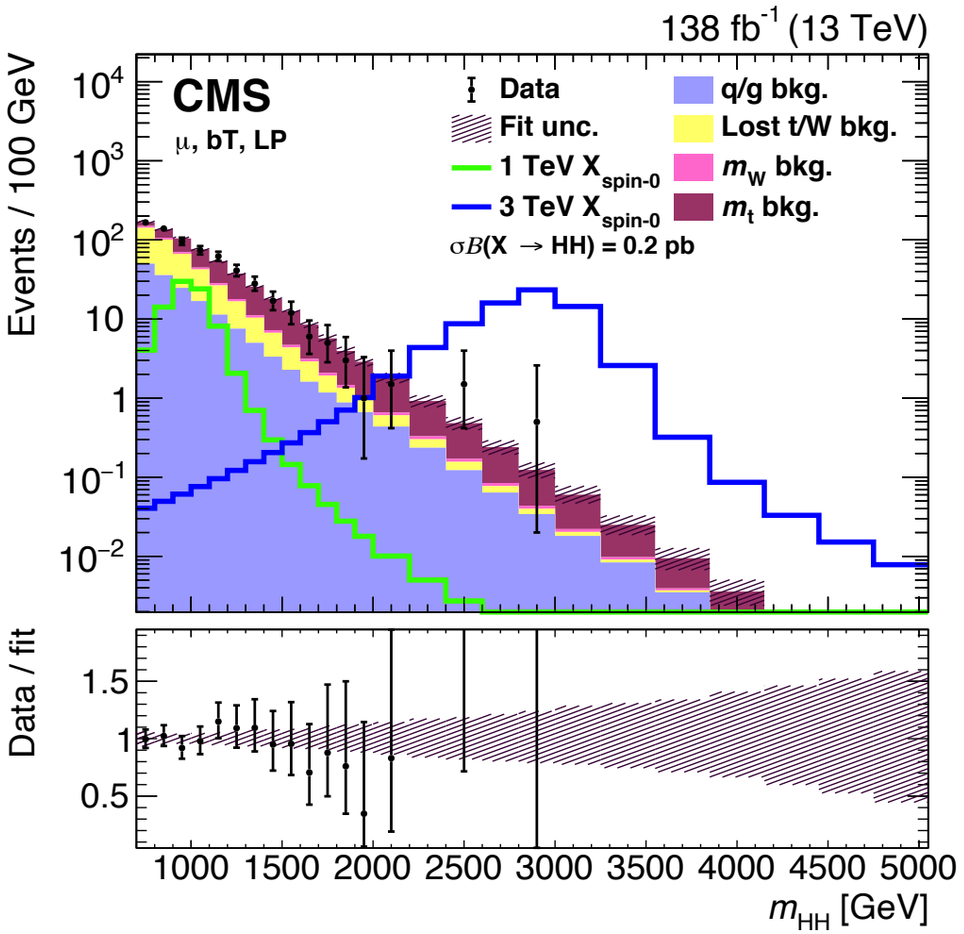




B2G-20-004

H→hh→bbWW

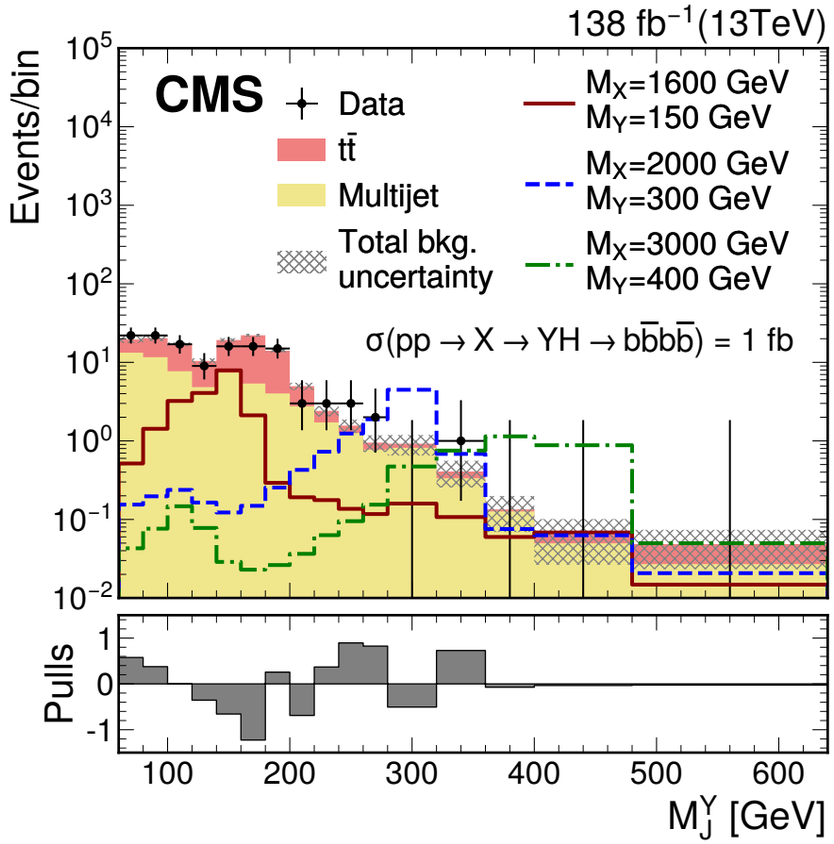
- Search for bbWW final state
- WW pair decays to 1 or 2 leptons
- Signal also includes contribution from h→$\tau\tau$→ lvlv
- 2b's merged into single AK8 jet - identified using DNN
- W→qq decays also merged into AK8 jets

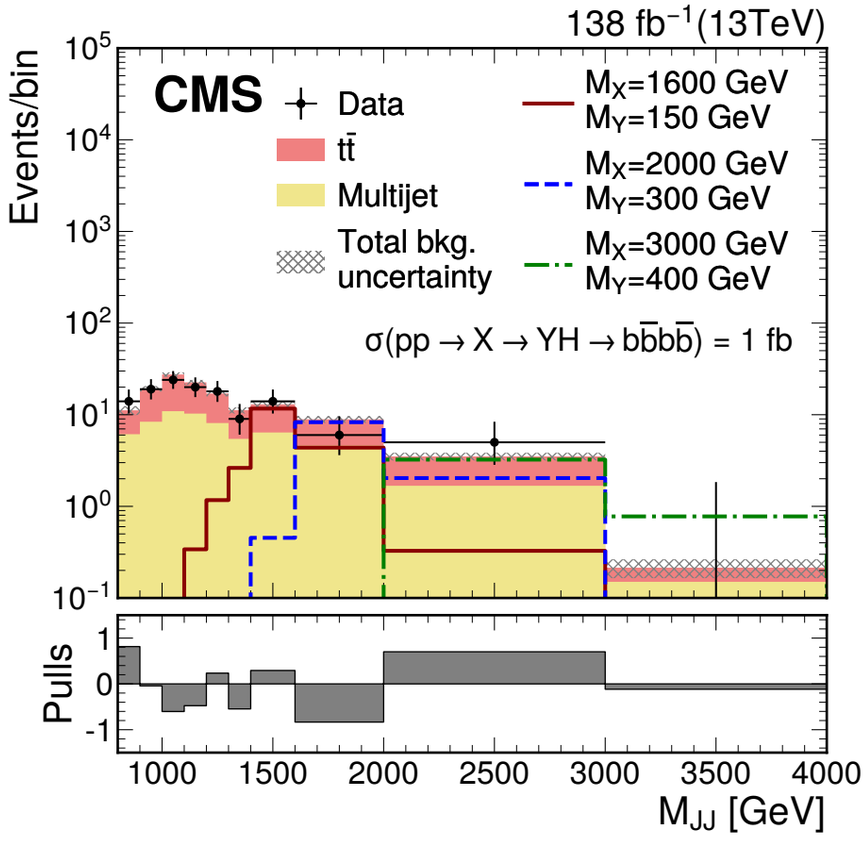


B2G-20-007

X→Yh→bbbb (boosted)

- Each bb pair reconstructed at large R jet (AK8)
- ParticleNet algorithm used to identify bb jets
- One jet required to have mass consistent with 125 GeV
- 2D fit of m_X and m_Y reconstructed masses



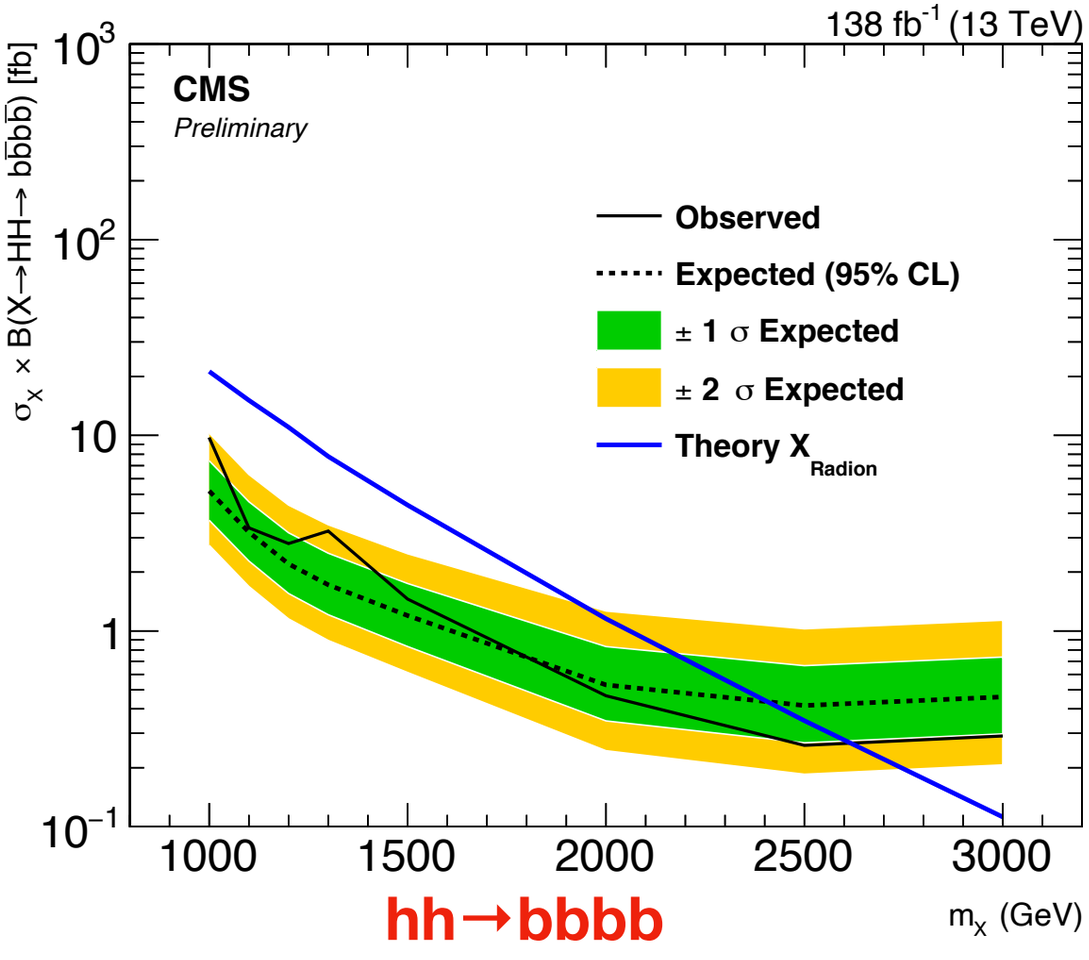


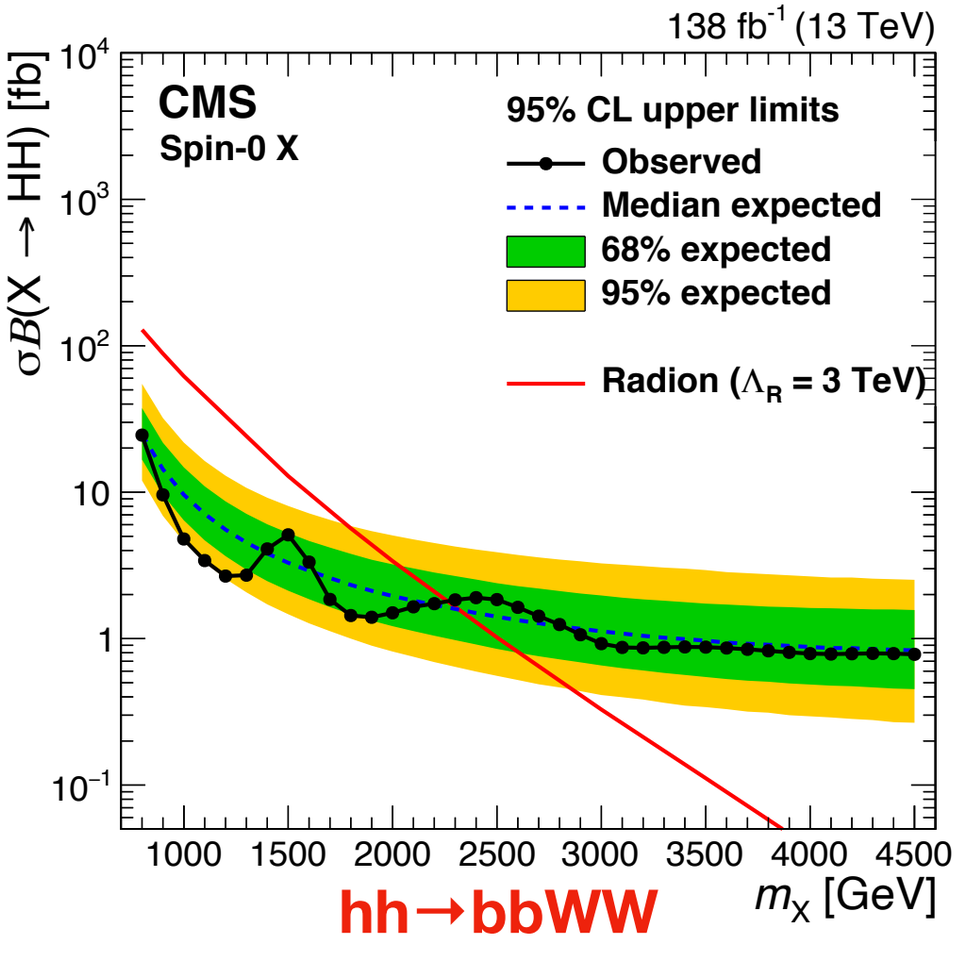
B2G-21-003

H→hh→bb + bb/WW

- CMS has also searched for boosted bbbb final state and boosted/ semi-resolved bbWW

- No significant excesses observed, so limits set of cross-sections





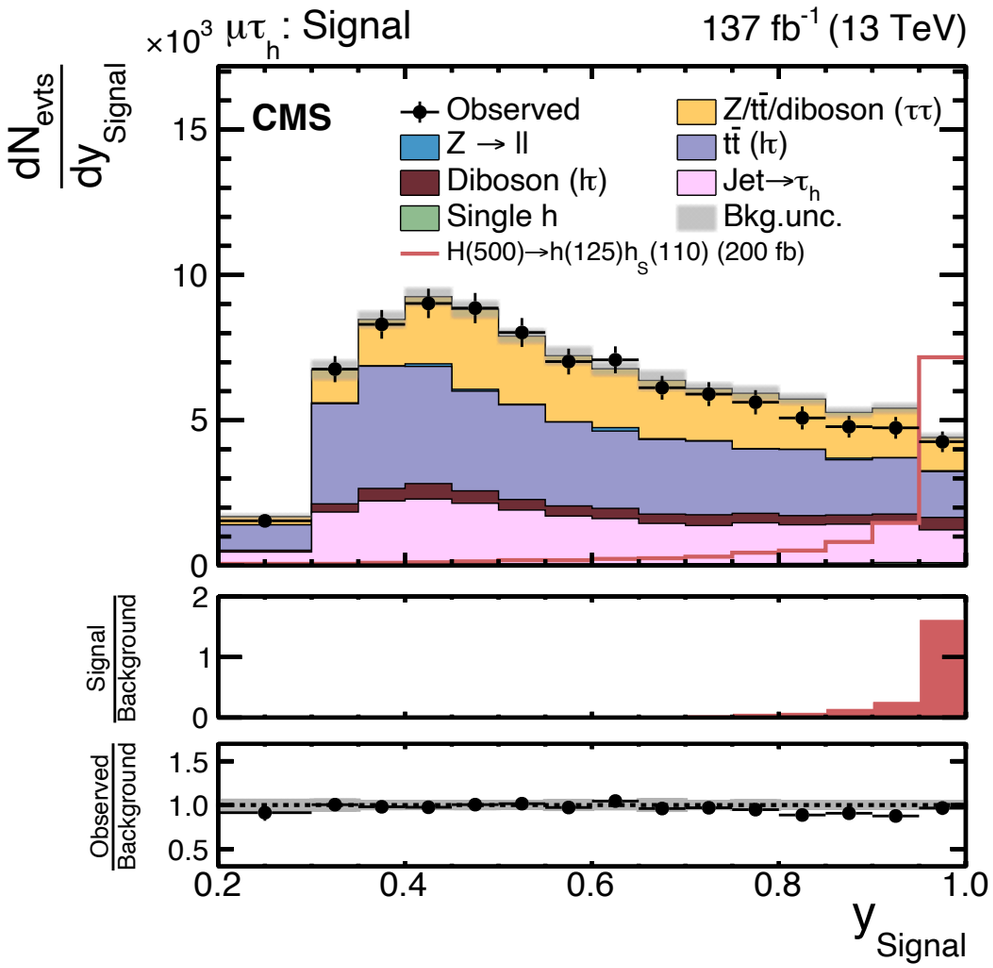
B2G-20-004

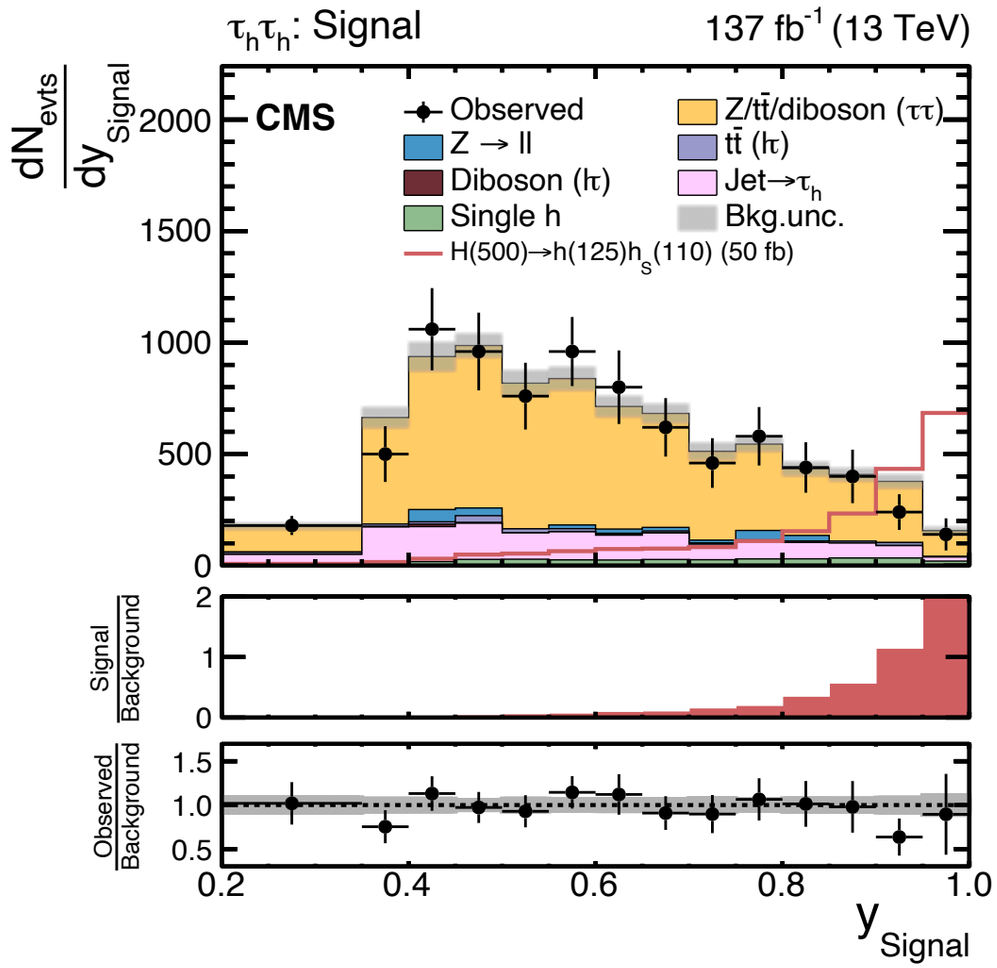
B2G-20-007

X→Yh→bb$\tau\tau$

- Target events with $\tau_h\tau_h$, $\mu\tau_h$, $e\tau_h$ candidates and 2 jets (at least 1 is b-tagged)

- Use NN to separate signal from backgrounds





HIG-20-014

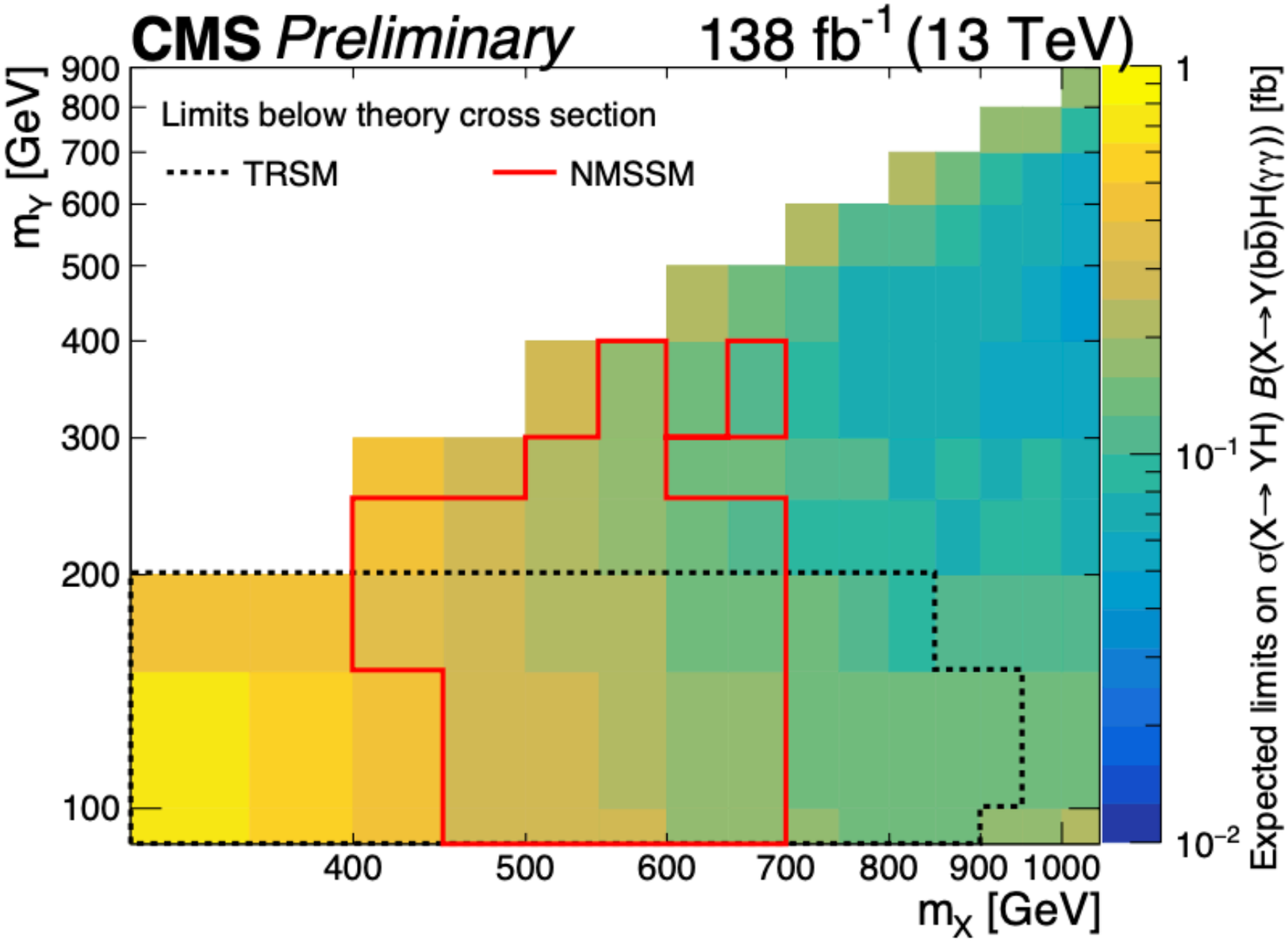
X→Yh→bb$\tau\tau$: NN variables

- Use NN to separate signal from backgrounds, using variables:
- p_T of τ candidates and b-jets
- Mass and p_T estimates of the $\tau\tau$ pair, the bb pair, and the bb$\tau\tau$ system
- N_{bjets} and kinematic properties of the jets
- Output scores of the b-tagger classifier
- Separate NNs trained for different mass regions

HIG-20-014

H→Yh→bbɣɣ

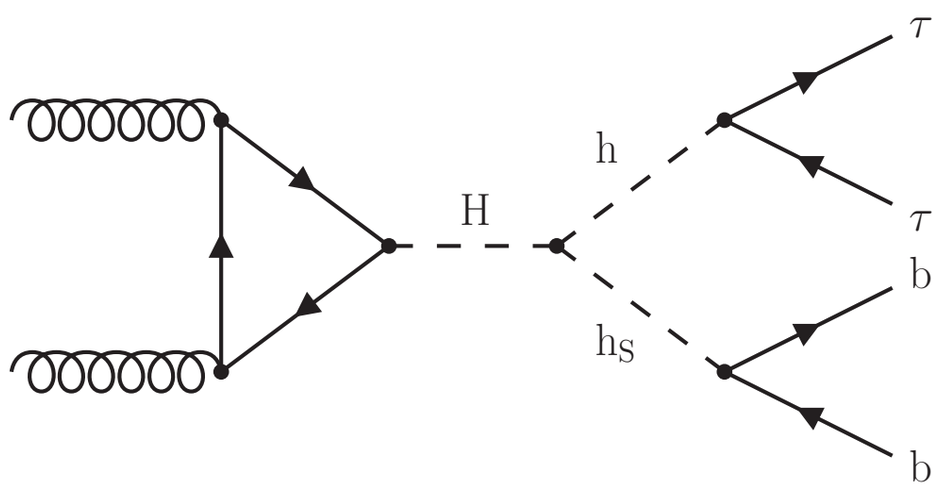
- Comparison of observed limits to most optimisitic cross sections for TRSM and NMSSM



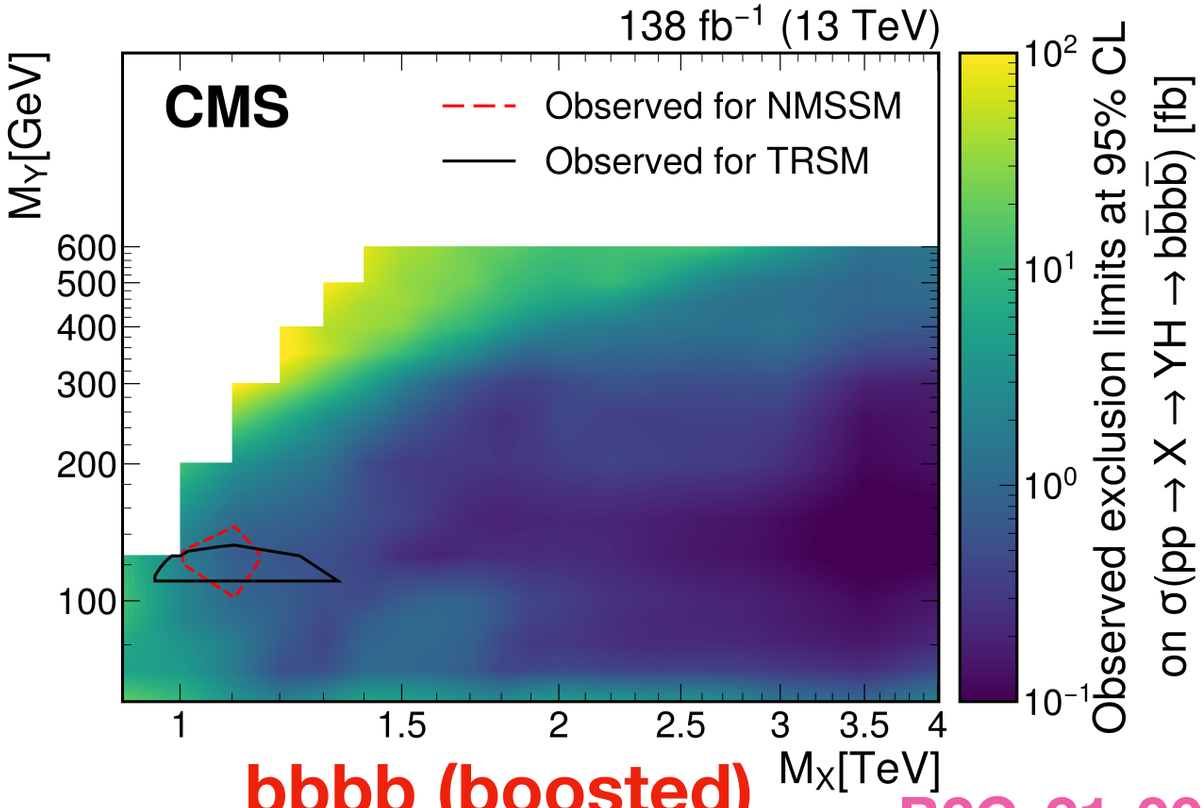
HIG-21-011

X→Yh

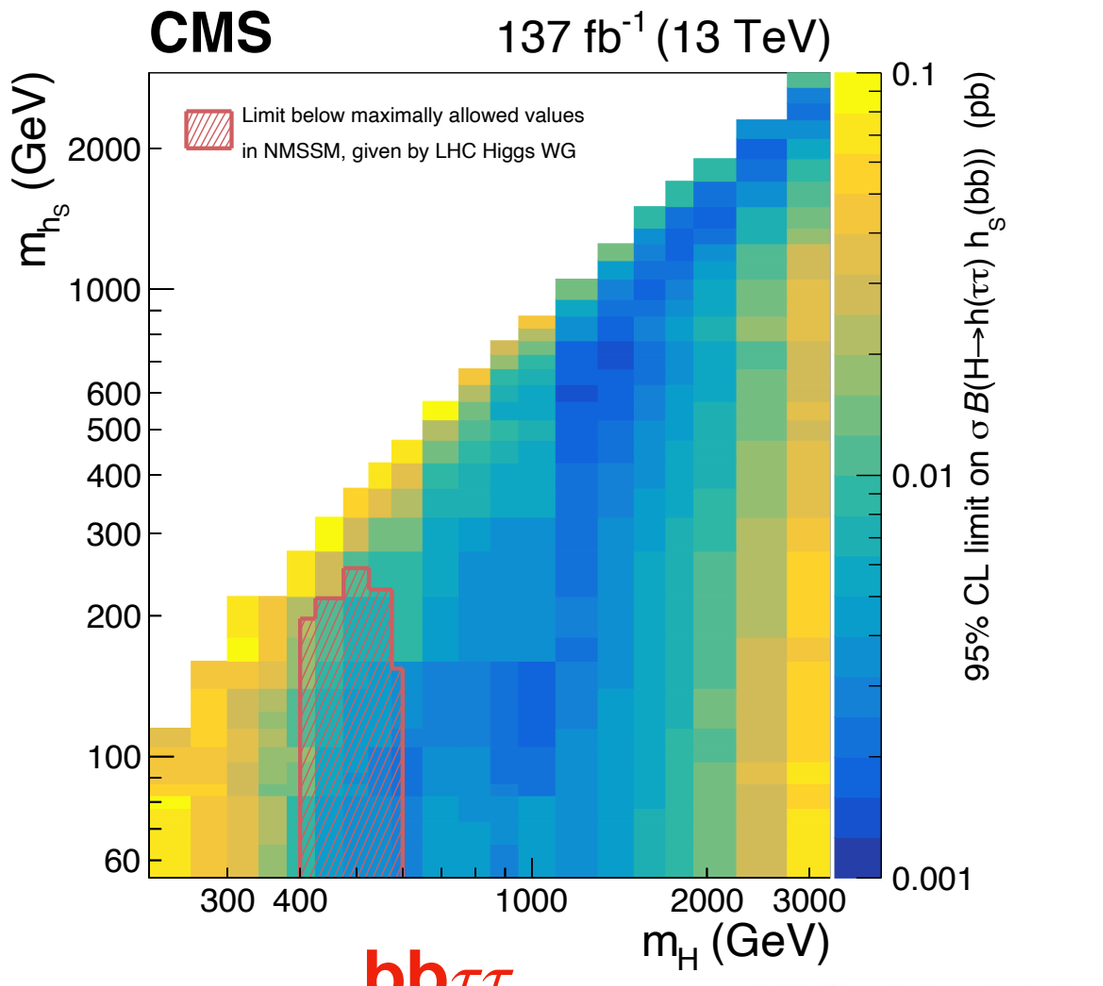
- Searched for X→Yh well motivated in models such as NMSSM
  - H decays to h(125) and singlet-like scalar (h_s)



- CMS have searched 4b (boosted) and bb$\tau\tau$ final states



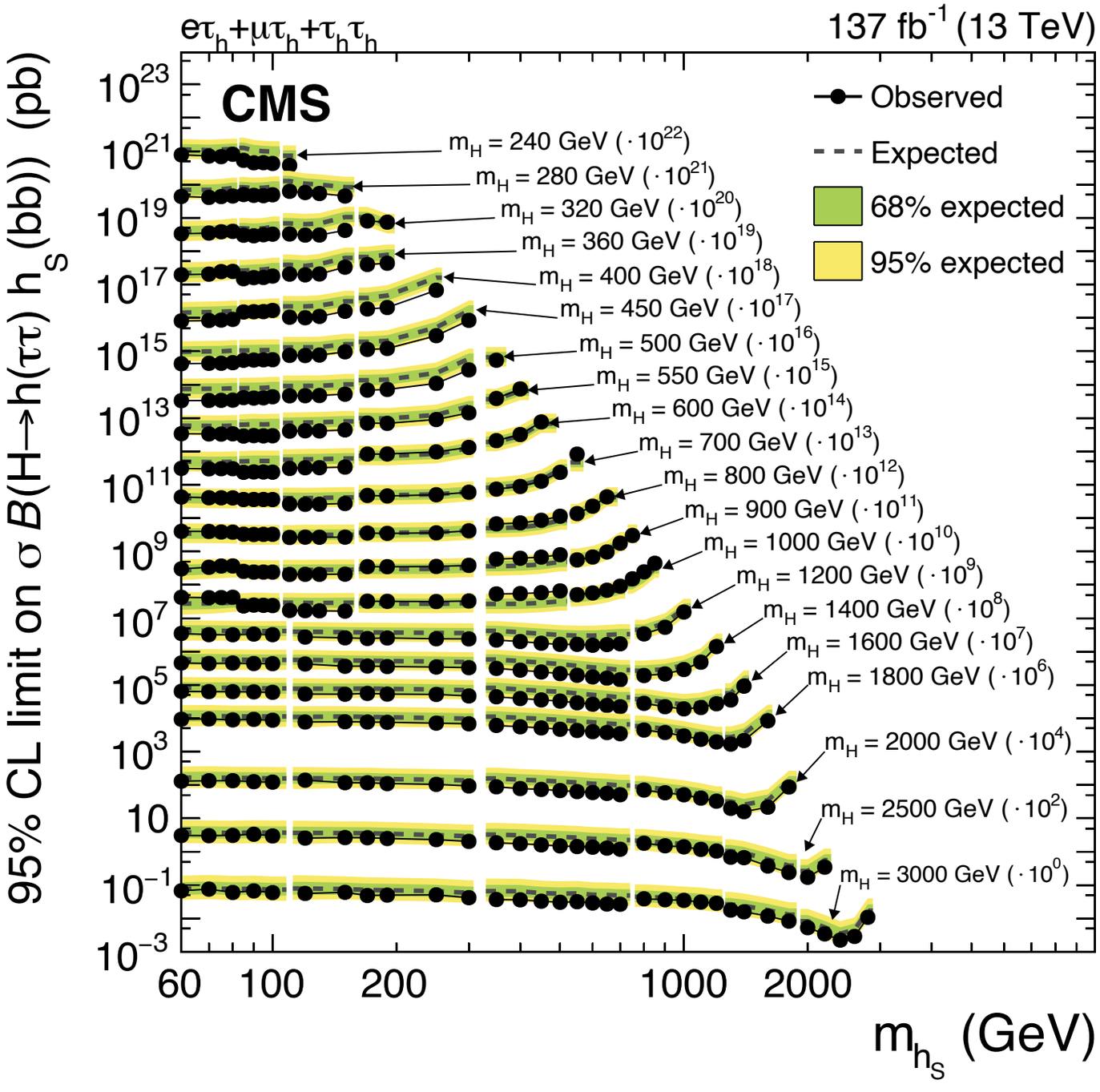
bbbb (boosted) [B2G-21-003]



bb$\tau\tau$ [HIG-20-014]

X→Yh→bb$\tau\tau$

- Limits on cross section times branching ratio for bb$\tau\tau$ final state



HIG-20-014

$H^{\pm} \to WH$, $H \to \tau\tau$: BDT variable

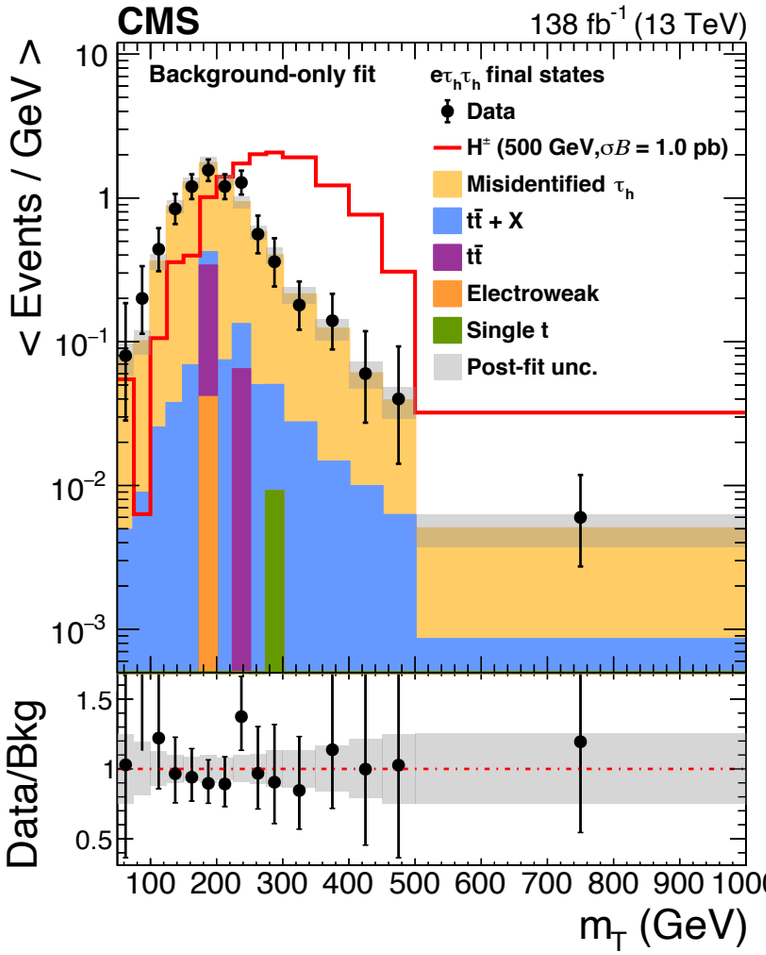
- BDT used to separate signal from background in lτ_h channels

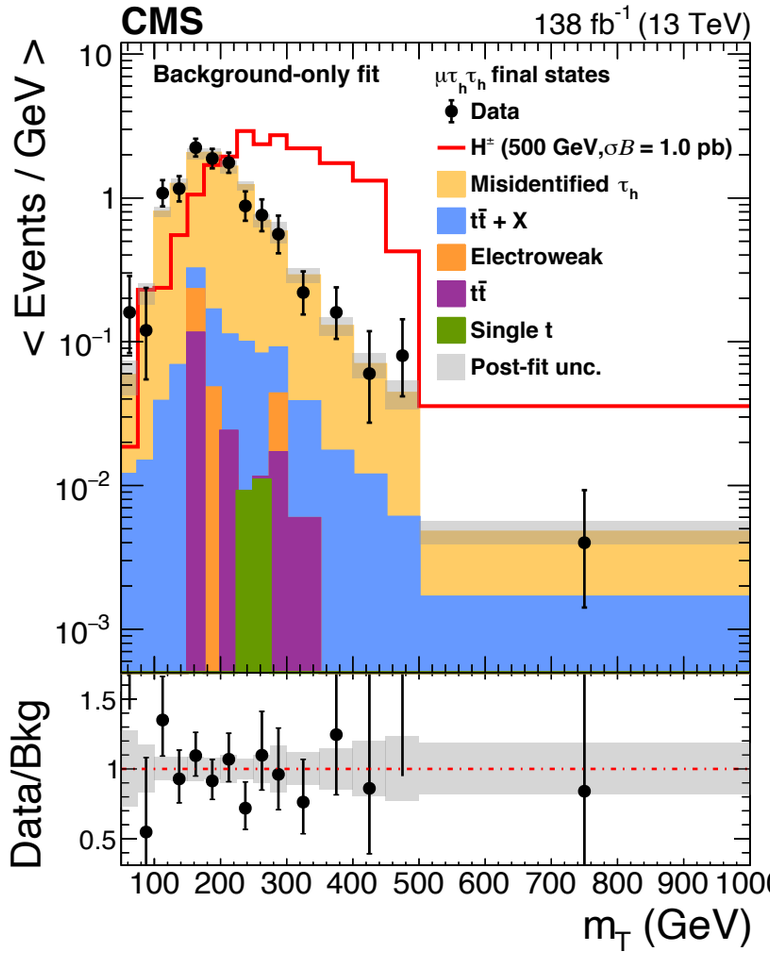
- Separate trainings for different mass hypotheses

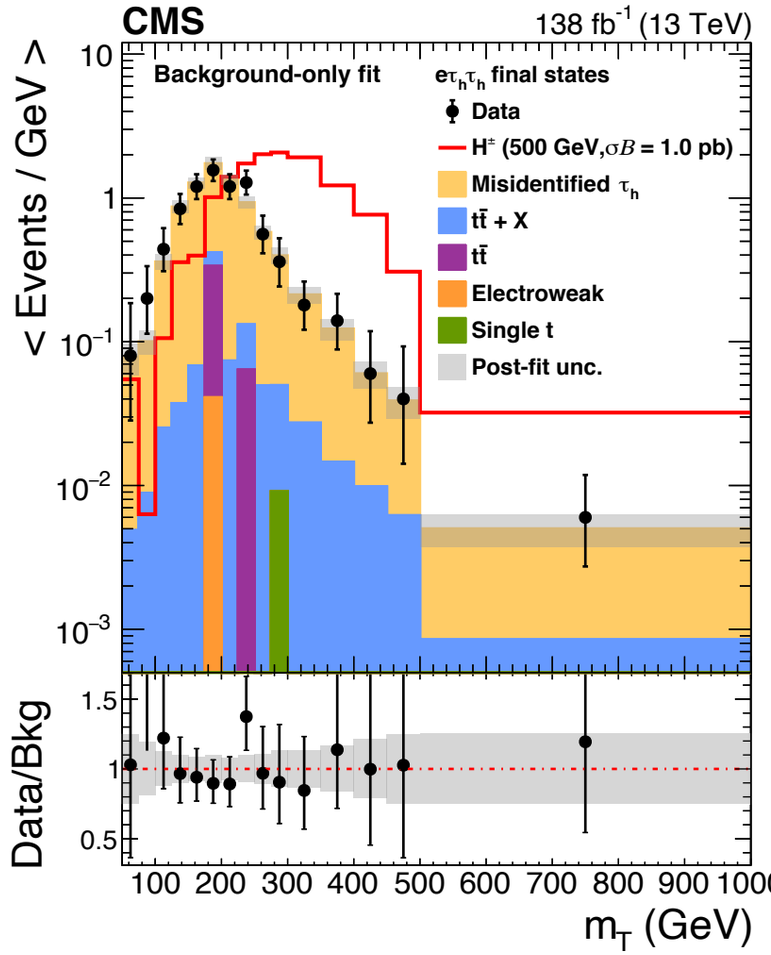
Variable	Description
$\Delta\phi(\tau_h, \vec{p}_T^{\,miss})$	azimuthal angle between the τ_h and $\vec{p}_T^{\,miss}$ objects
$\Delta\phi(\ell, \vec{p}_T^{\,miss})$	azimuthal angle between the ℓ and $\vec{p}_T^{\,miss}$ objects
$\frac{p_T^{j_1 j_2} - p_T^{H^{\pm}}}{p_T^{j_1 j_2} + p_T^{H^{\pm}}}$	ratio of p_T sums calculated from ℓ, τ_h, j_1, j_2 and $\vec{p}_T^{\,miss}$
$\frac{p_T^{j_1 j_2}}{H_T}$	ratio of p_T of the first two leading jets and the H_T
$m_T(\ell, \tau_h, j_1, j_2, \vec{p}_T^{\,miss})$	m_T reconstructed from ℓ, τ_h, j_1, j_2, and $\vec{p}_T^{\,miss}$
$\frac{p_T^{j_3}}{H_T}$	ratio of the p_T of the third leading jet and the H_T
$m(\ell, \tau_h)$	invariant mass of the ℓ and τ_h objects
$\frac{p_T^{j_1 j_2} + L_T}{H_T}$	ratio of p_T of first two leading jets plus L_T and the H_T
$m_T(\ell, \vec{p}_T^{\,miss})$	m_T reconstructed from the ℓ and $\vec{p}_T^{\,miss}$ objects
$p_T^{\tau_h}$	transverse momentum of τ_h object
N_{jets}	number of selected jets in the event
$N_{t^{res}}$	number of selected t^{res} objects in the event

HIG-21-010

$H^{\pm} \rightarrow WH, H \rightarrow \tau\tau$: Other fitted distributions



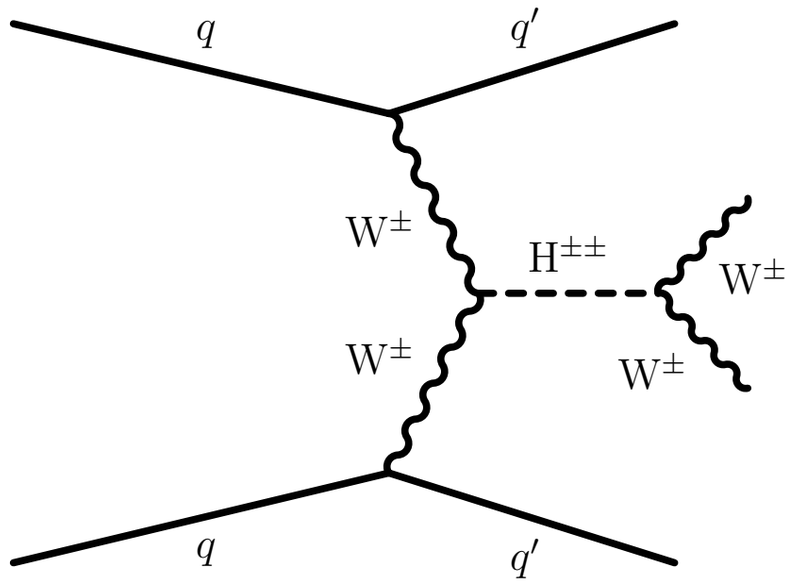


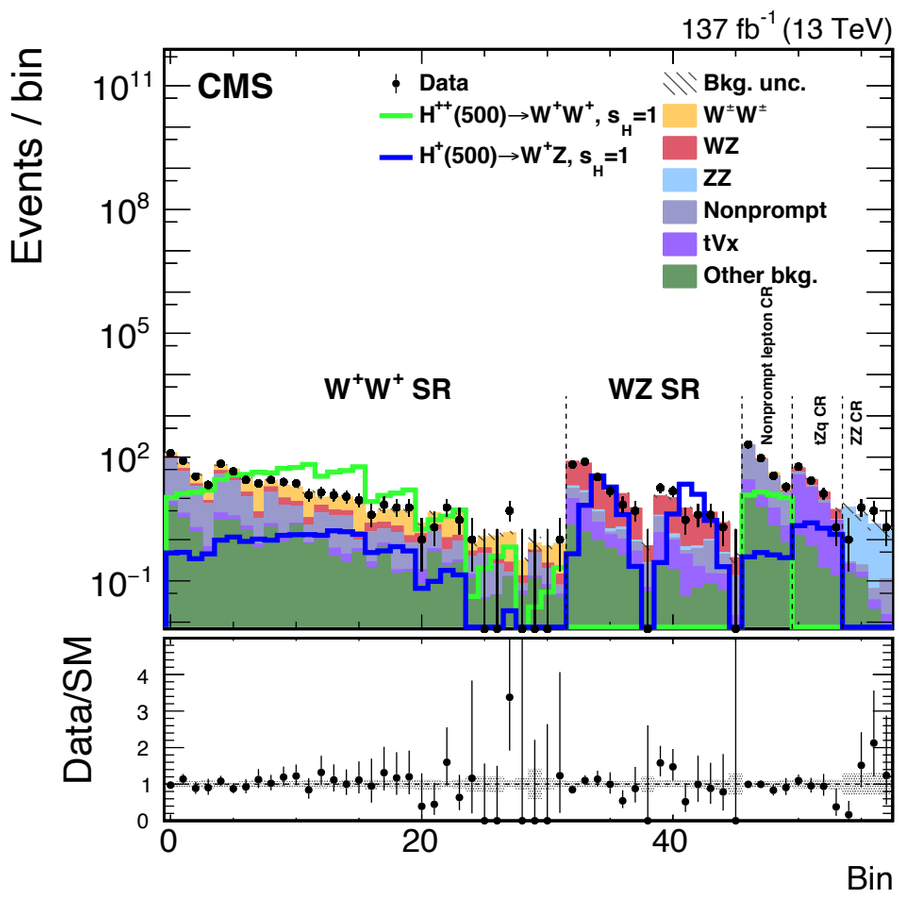


HIG-21-010

$H^{\pm(\pm)} \rightarrow WZ$ (WW)

- Search for $H^{\pm(\pm)}$ in WZ or WW final states produced by VBF
- Select events with 2 jets to tag VBF
- 2 or 3 leptons required in final states + missing p_T
- Fit 2D distribution m_{jj} vs m_T to extract results
- Motivated by models with additional SU(2) triplets
  - Get singly and doubly charged Higgs' that couple to W and Z bosons at tree level
  - e.g Georgi–Machacek model

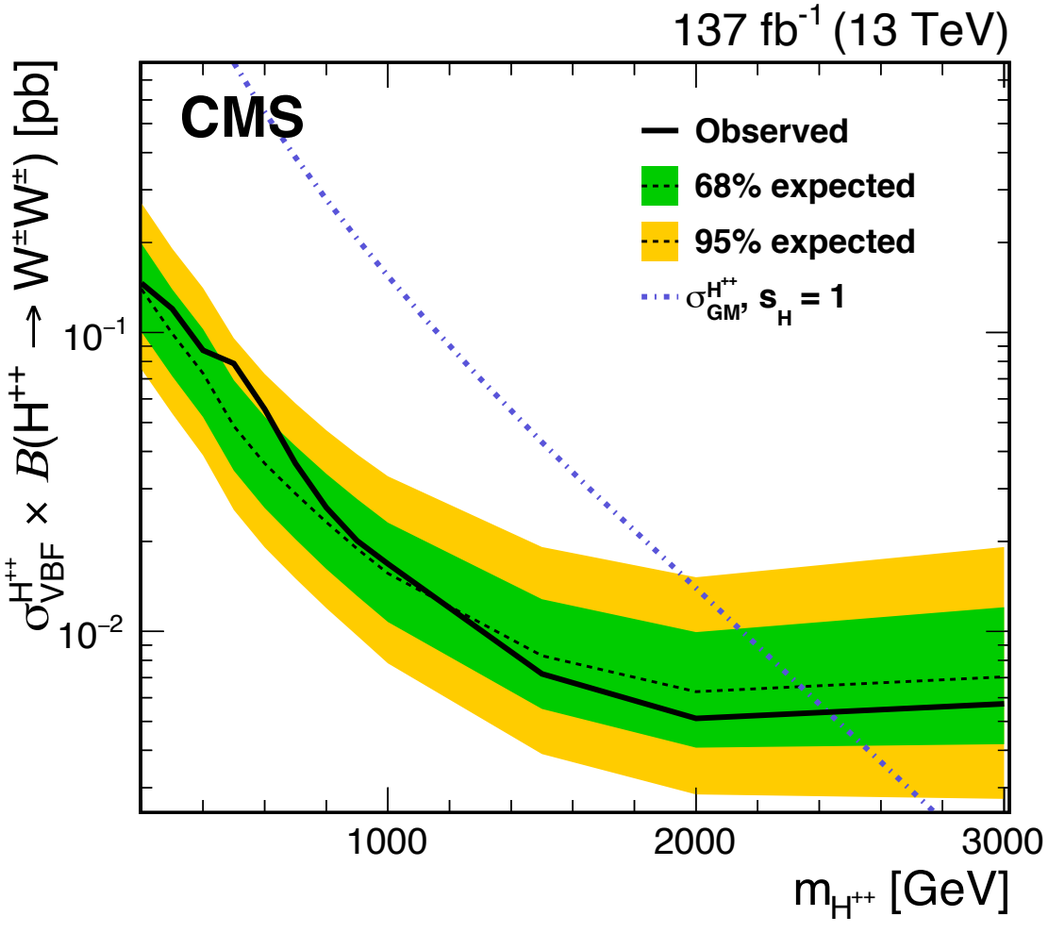


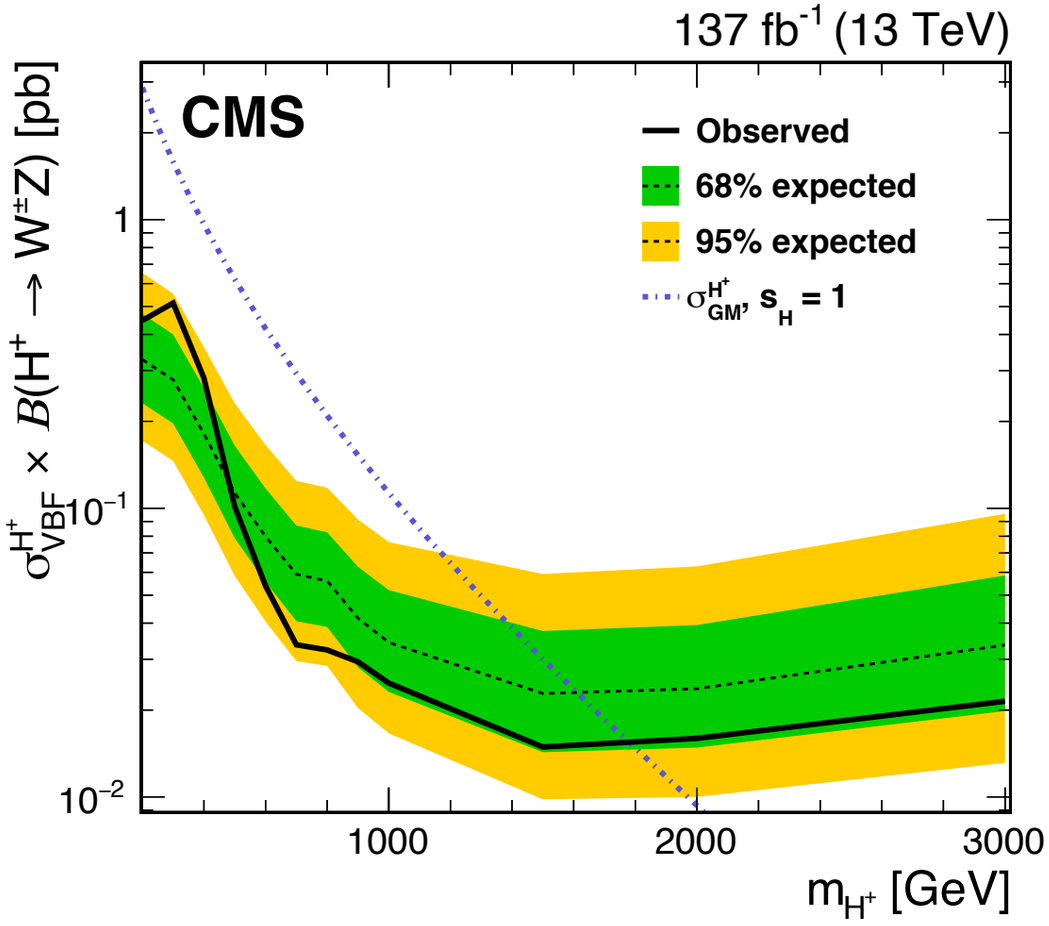


HIG-20-017

$H^{\pm(\pm)} \rightarrow WZ$ ($W^{\pm}W^{\pm}$)

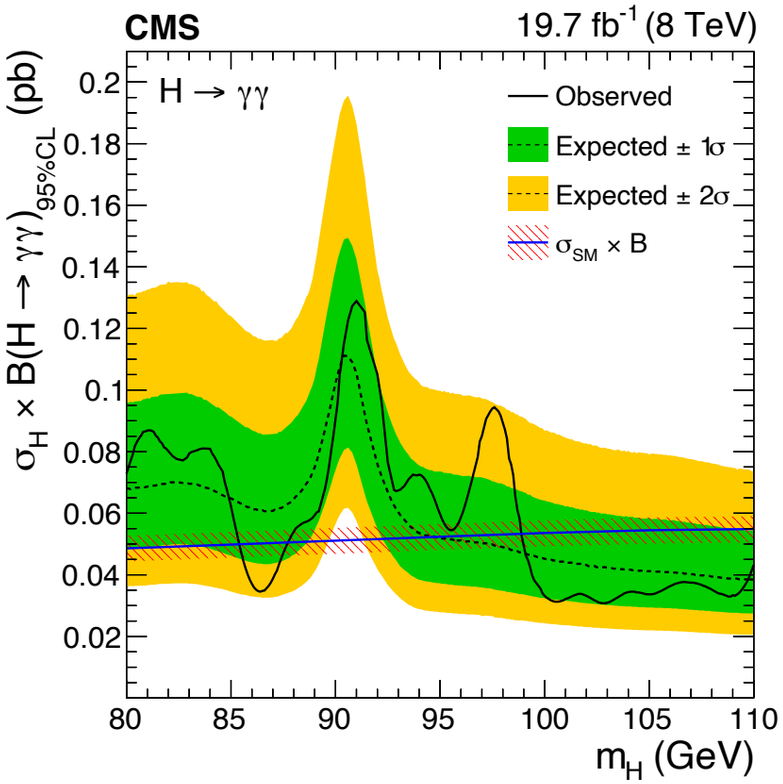
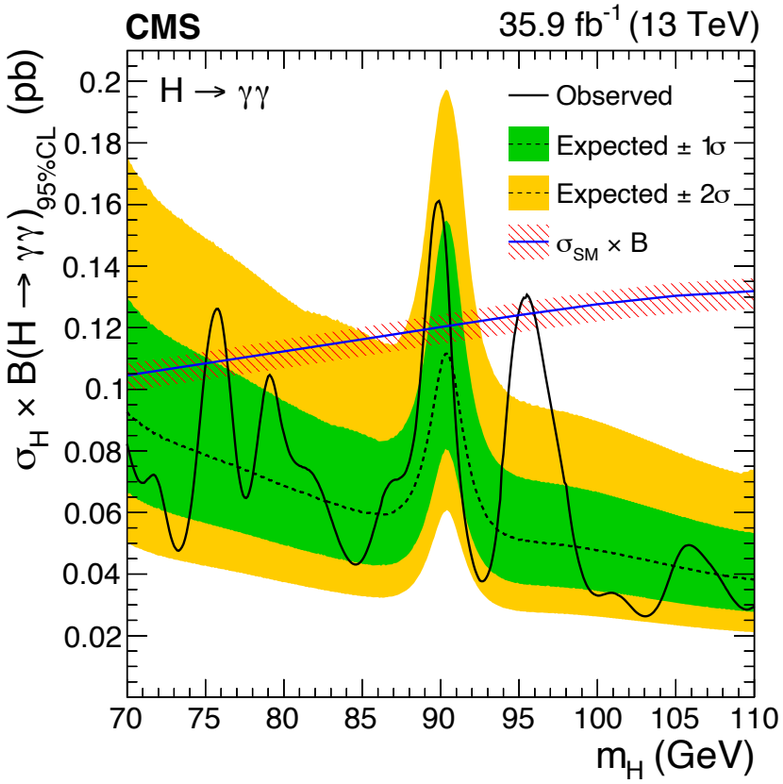
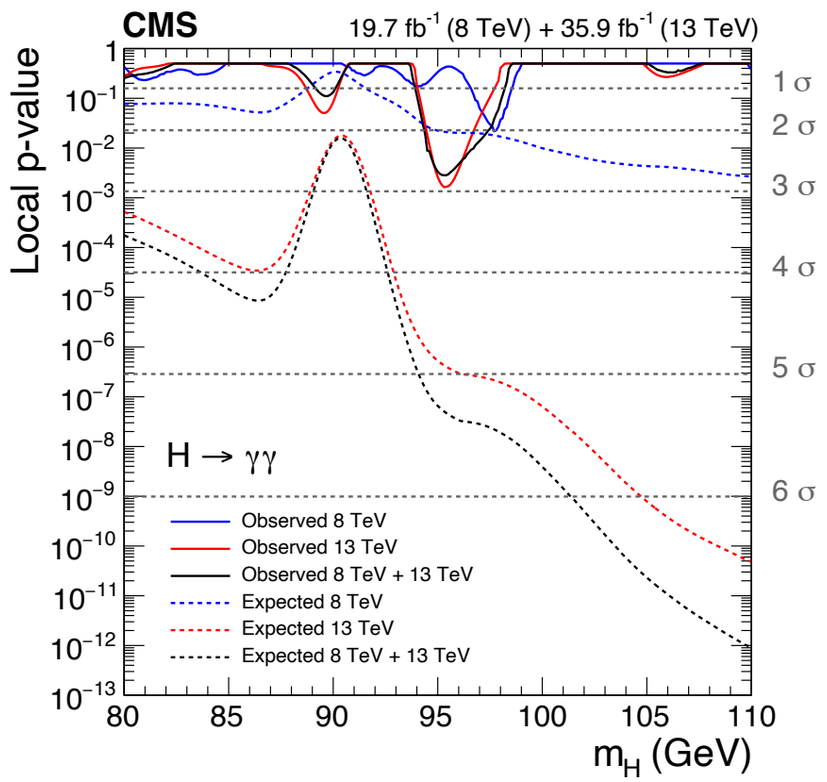
- CMS has also searched for charged and doubly charged Higgs in WZ and $W^{\pm}W^{\pm}$ final state
- Production process is VBF
- No excess observed, limits set on cross-sections





HIG-20-017

Low mass H→γγ analysis

- Analysis performed using only Run 1 (19.7 fb^{-1}) and Run 2 data collected in 2016 (35.9 fb^{-1})

- Excess with local (global) significance of 2.8 (1.3)σ @ 95.3 GeV