

Additional Scalar Bosons

CMS

Higgs Hunting 2022

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Introduction

Higgs sector in Beyond Standard Model

- Higgs sector is extended in many BSM models
- Minimal extension is known as the Two-Higgs-Doublet Model (2HDM). Key parameters:
 - **Mass values** of five predicted Higgs bosons: H , h , A , H^+ and H^-
 - α : mixing angle which diagonalises the neutral scalar mass matrix;
 - $\tan\beta$: the ratio of vacuum expectation values of the two Higgs doublets
- Other extensions predict extra scalars: **MSSM** (Type-II 2HDM), **NMSSM**, **TRSM** ...
- Recent searches for additional scalars in CMS using **full Run 2** dataset with 138 fb^{-1} integrated luminosity

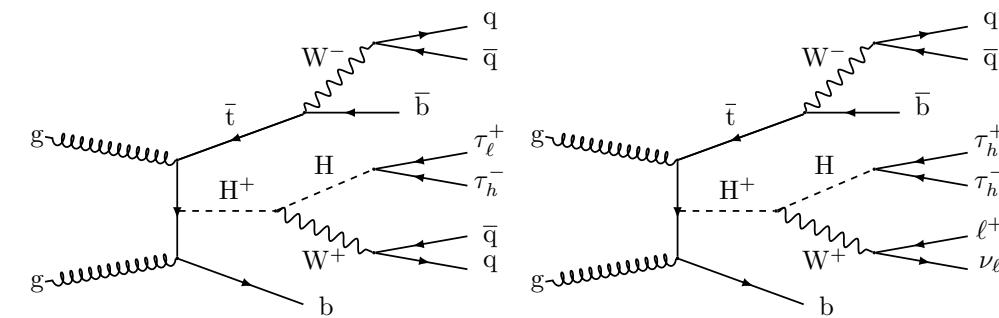
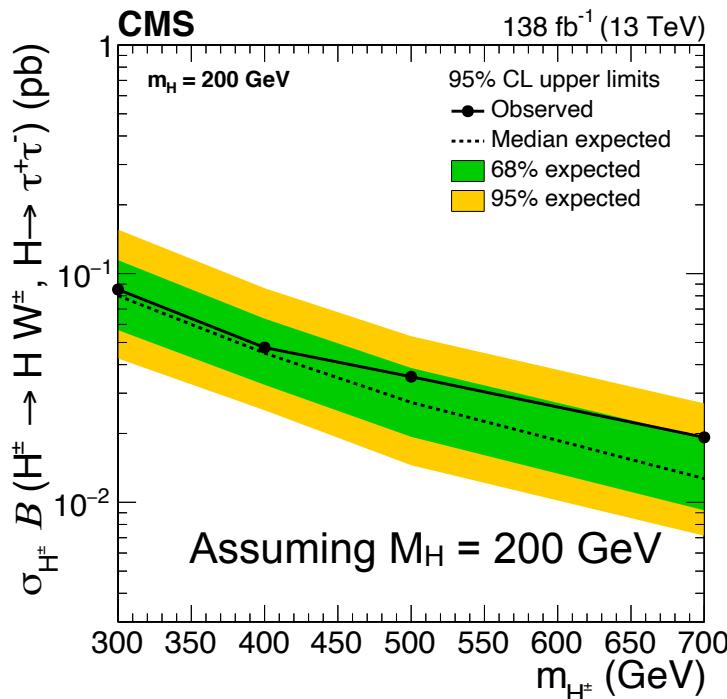
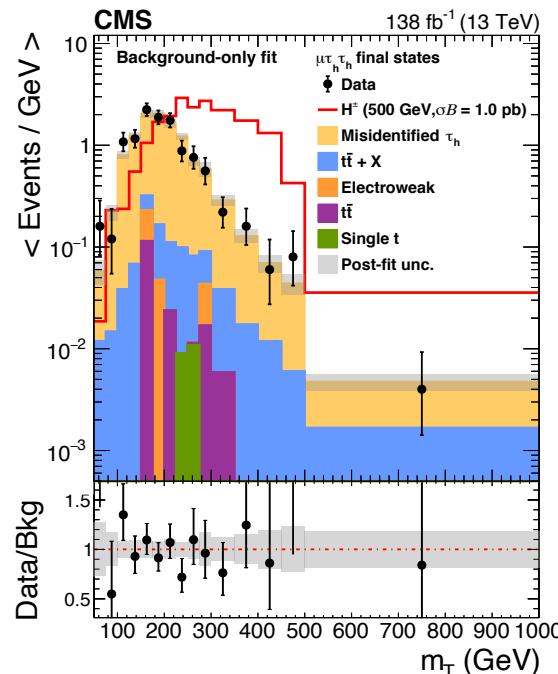
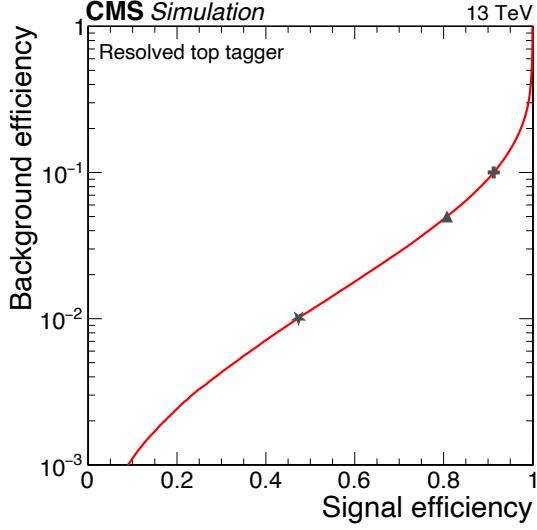
Model	Channel	Reference
2HDM	$H^+ \rightarrow H W^+$	arXiv:2207.01046
MSSM	$\phi \rightarrow \tau\tau$	arXiv:2208.02717
2HDM/MSSM	Heavy $H \rightarrow W^+W^-$	CMS-PAS-HIG-20-016
NMSSM + TRSM	$X \rightarrow YH \rightarrow b\bar{b}\gamma\gamma$	CMS-PAS-HIG-21-011
	$X \rightarrow YH \rightarrow bbbb$	arXiv:2204.12413
Singlet scalar	$V\phi, tt\phi, \phi \rightarrow ll/\tau\tau$	CMS-PAS-EXO-21-018

Di-Higgs: see Marcel's talk
BSM decays: see Maxime's talk

2HDM: $H^+ \rightarrow H W^+$

arXiv:2207.01046

- Search for **heavy** mass region of H^+ : **300-700 GeV**
- Dominant mode of H^+ : **Produced with a top quark and a b-quark**
- Consider four final states of Heavy Higgs H and W : **$e\tau_h$, $\mu\tau_h$, $e\tau_h\tau_h$ and $\mu\tau_h\tau_h$**
- NN-based resolved **top tagger** to tag top quark jet: 90% efficiency vs. 10% of misidentification rate
- Dominant backgrounds: Jet misidentified as hadronic tau, $t\bar{t}X$ ($X = W, Z$ and h)
- **BDT score** ($e\tau_h$, $\mu\tau_h$) and **transverse mass** ($e\tau_h\tau_h$, $\mu\tau_h\tau_h$) as signal discriminants

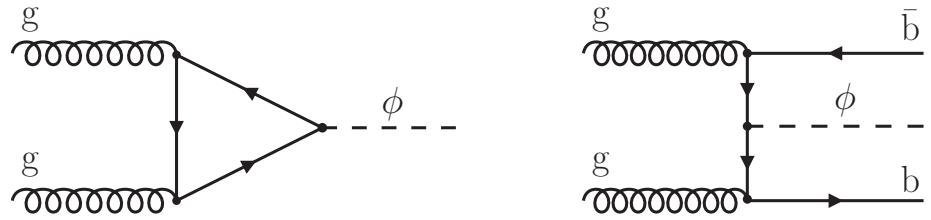


Conclusions:

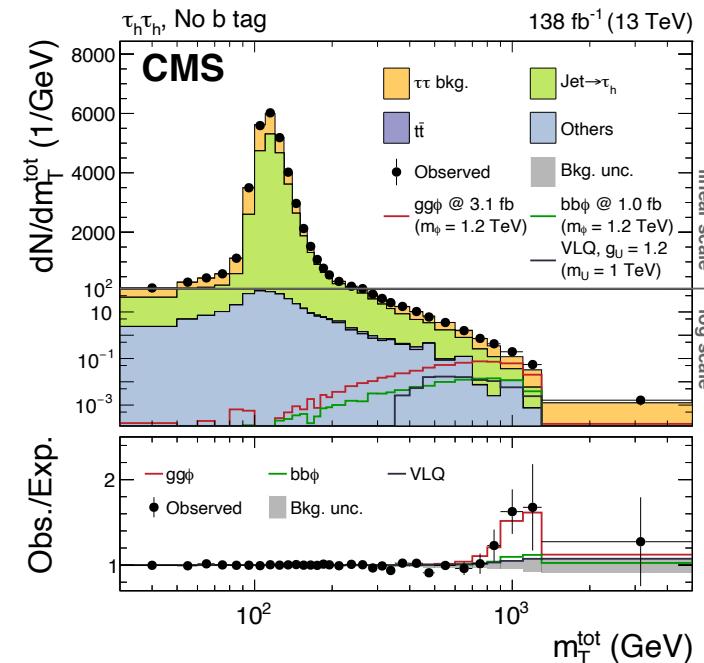
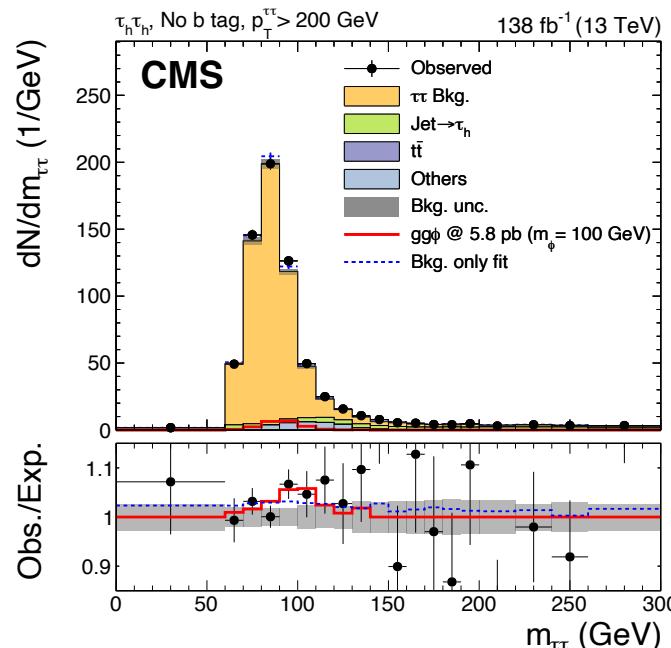
- No deviation from the SM
- First limits on this decay channel at the LHC

MSSM: $\phi(h, H, A) \rightarrow \tau\tau$

arXiv:2208.02717



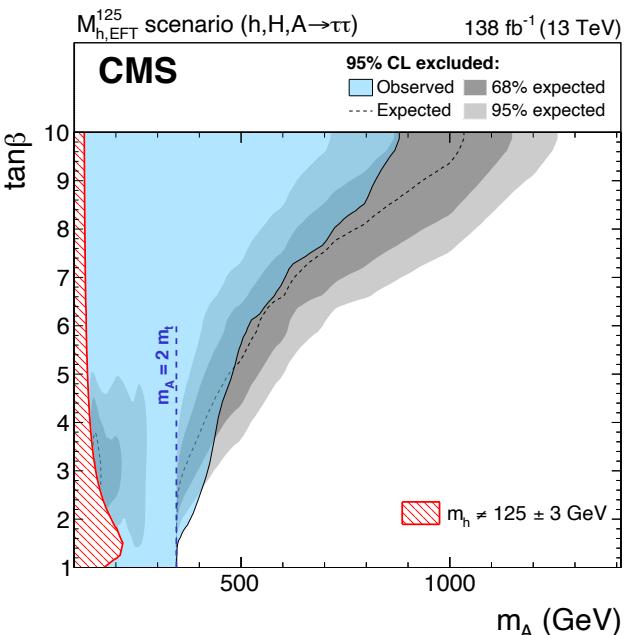
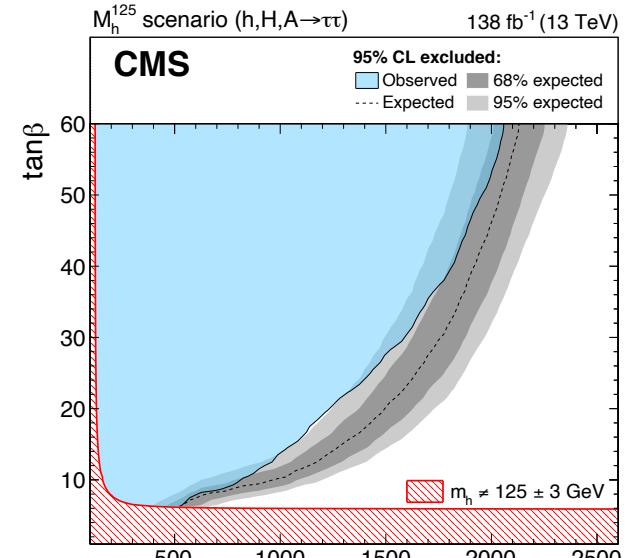
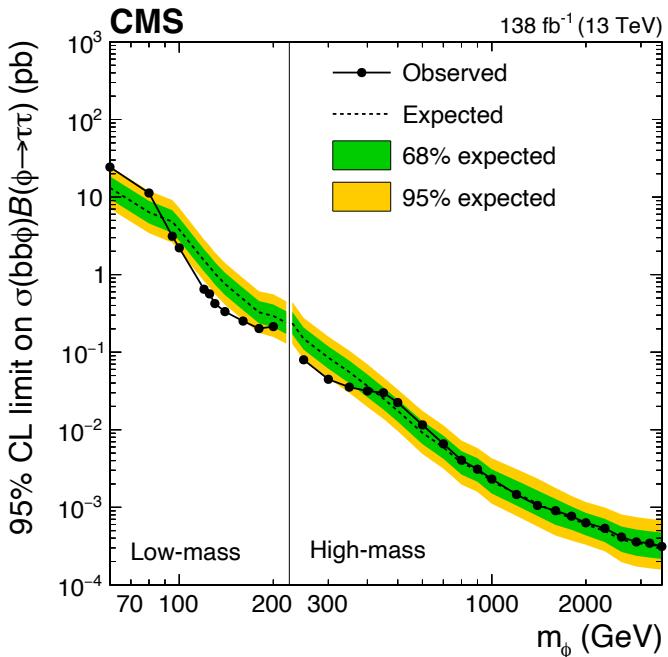
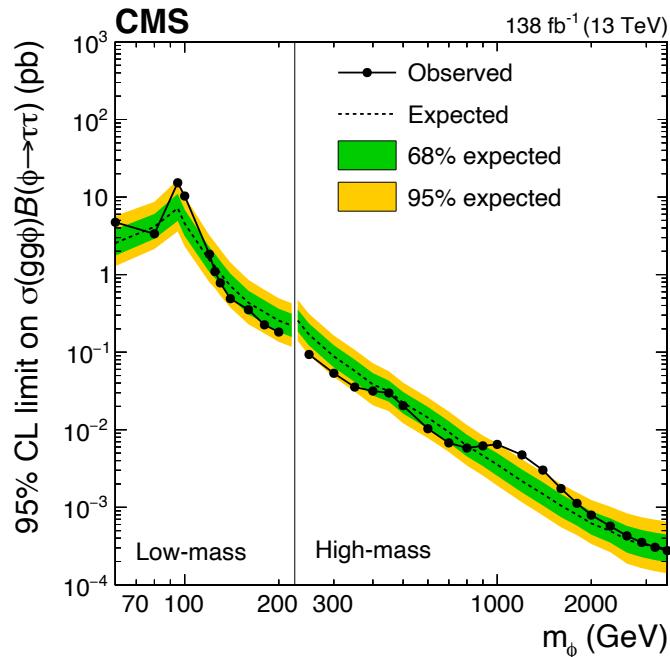
- Targeting **ggφ** and **bbφ** production for **low-mass** (60 - 250 GeV) search and **high-mass** (250 - 3500 GeV) search
- Four final states of $\phi \rightarrow \tau\tau$: **eμ, eτh, μτh and τhτh**
- p_T of $\tau\tau$ system, D_ζ and transverse mass of light lepton to categorise events
- Use of number of b-tagged jets in an event to target different production modes
- Data-driven estimation **~ 95% of the backgrounds**: τ -embedded for genuine $\tau\tau$, fake factor method for jet $\rightarrow \tau$
- Signal discriminants: a kinematic fit built mass **$M_{\tau\tau}$ for low-mass search**, and **total transverse mass for high-mass search**



MSSM: $\phi(h, H, A) \rightarrow \tau\tau$

arXiv:2208.02717

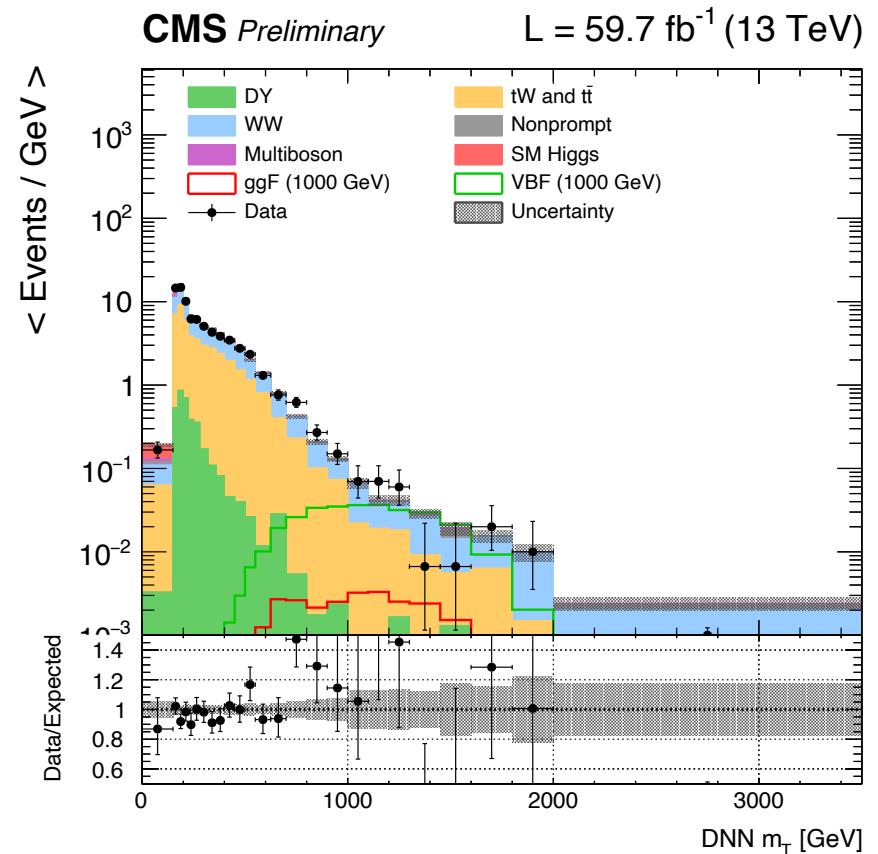
- **Model independent limits:** GG ϕ and bb ϕ , for low-mass and high-mass
- Model dependent limit for MSSM M_h^{125} and $M_{h,EFT}^{125}$ scenarios
- Conclusions:
 - Two excesses for gg ϕ production with local significance $\sim 3\sigma$ at 0.1 and 1.2 TeV
 - Additional Higgs bosons in MSSM benchmarks are **excluded** at 95% CL for masses **below 350 GeV**



2HDM/MSSM: heavy $H \rightarrow WW$

CMS-PAS-HIG-20-016

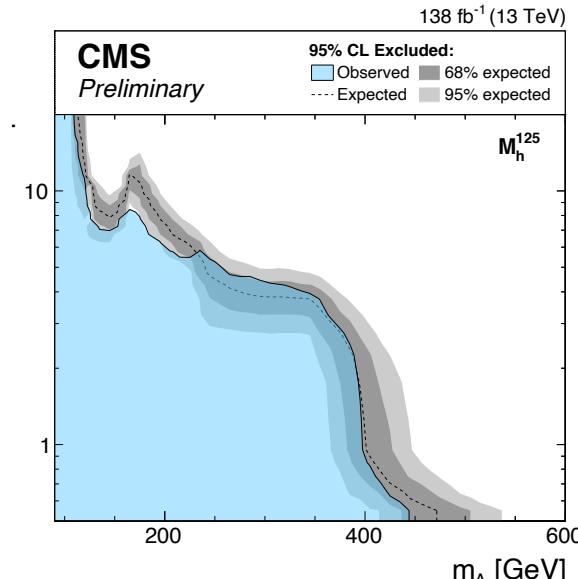
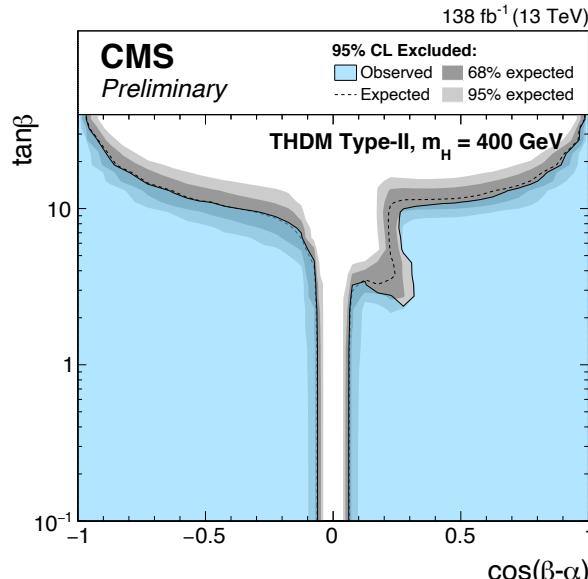
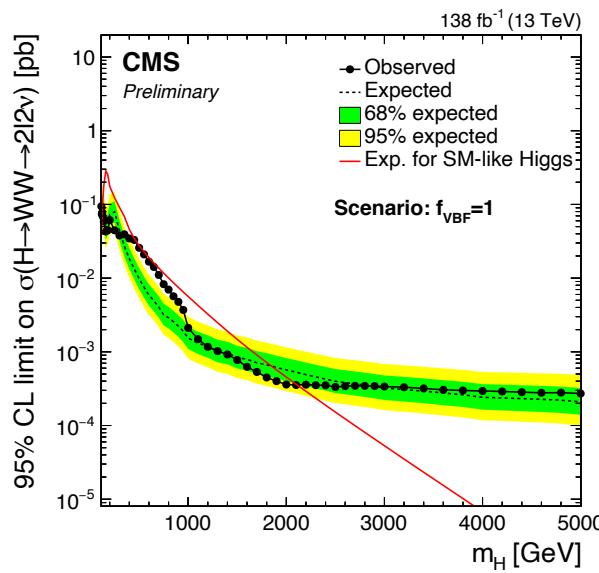
- Search for heavy Higgs in ggH and VBF H production modes from 150 - 5000 GeV
- $H \rightarrow WW \rightarrow e\mu, \mu\mu$ and ee fully leptonic final states
- Dominant backgrounds:
 - **Top and DY**. Estimated from MC and controlled by data
 - **SM WW processes**. Estimated from MC
 - **Jet misidentified as lepton**. Estimated from data-driven
- Use DNN to classify ggH, VBF H signals and the background events
- Signal discriminant: **a DNN trained transverse mass**
 - Use input variables that have impact on mass hypotheses
 - The output layer has a single node and uses a linear activation function



2HDM/MSSM: Heavy $H \rightarrow WW$

CMS-PAS-HIG-20-016

- Results are shown for **different f_{VBF}** , a ratio of ggF to VBF contribution, as well as **2HDM and MSSM benchmark scenarios**
- Conclusions:
 - Highest excess: 3.8 local significance at 650 GeV for $f_{VBF} = 1$, i.e., assuming only VBF production mode
 - **Presence of heavy Higgs excluded** up to
 - **2.1 TeV** assuming SM-like VBF contribution and also assuming only VBF contribution
 - **900 GeV** assuming only ggF contribution and also assuming f_{VBF} freely floating in the fit



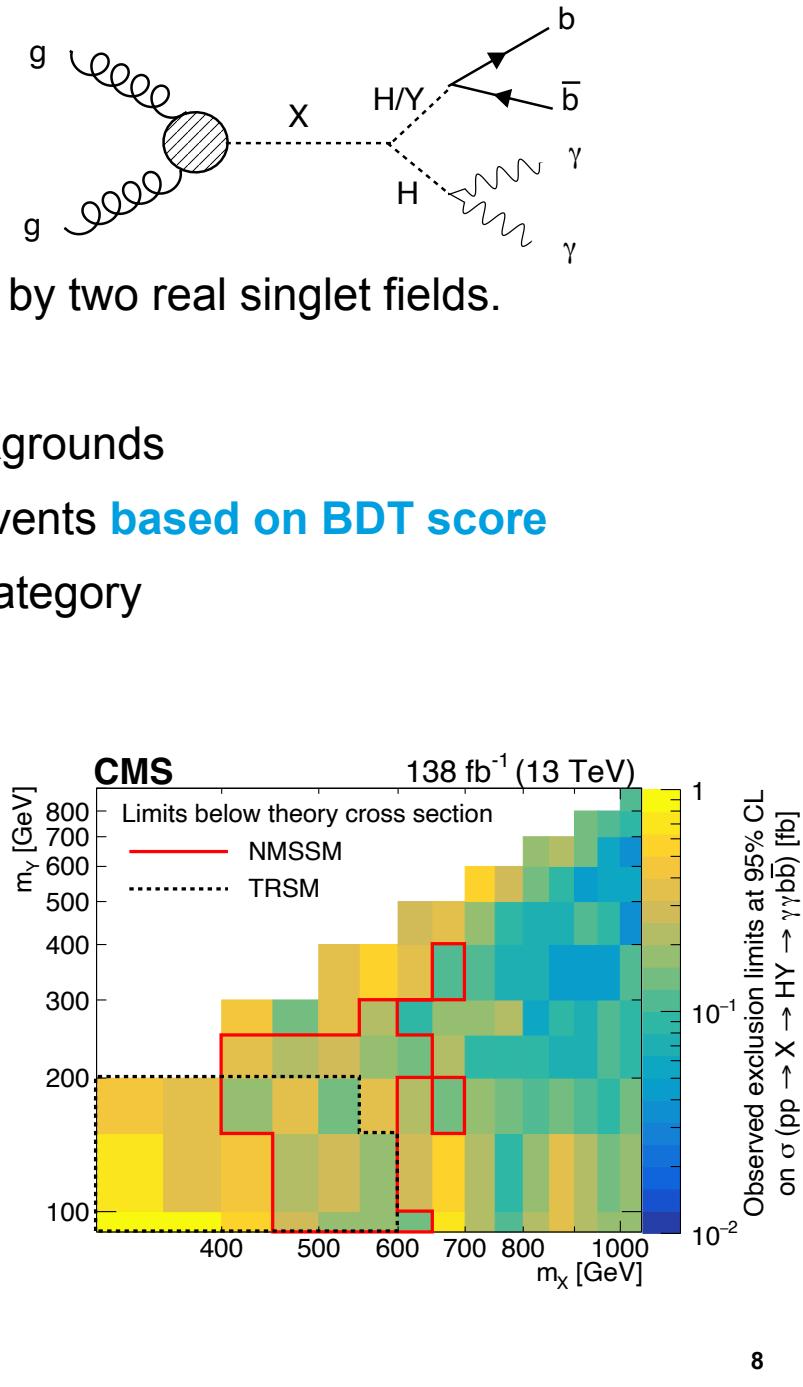
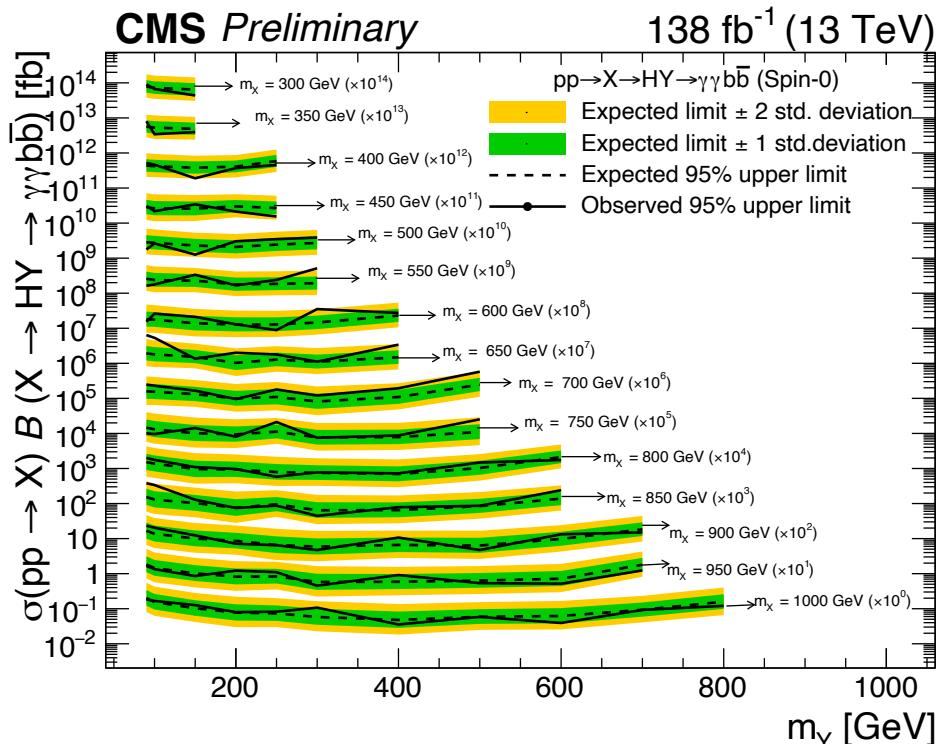
NMSSM, TRSM: $X \rightarrow YH \rightarrow b\bar{b}\gamma\gamma$

CMS-PAS-HIG-21-011

- NMSSM: MSSM extended by one more complex singlet. TRSM: SM extended by two real singlet fields.
- Heavy Higgs can decay to a lighter Higgs and SM H
- **BDT** (NN) score is used to separate signals and non-resonant (resonant) backgrounds
- Six BDT training accounts for different $m_X - m_Y$ mass differences; **Categorise events based on BDT score**
- **A parametric fit in the $(m_{\gamma\gamma}, m_{jj})$ plane** is used for signal extraction for each category

Conclusions:

- The largest deviation from SM with local significance of **3.8σ found for $(m_X, m_Y) = (650, 90)$ GeV**



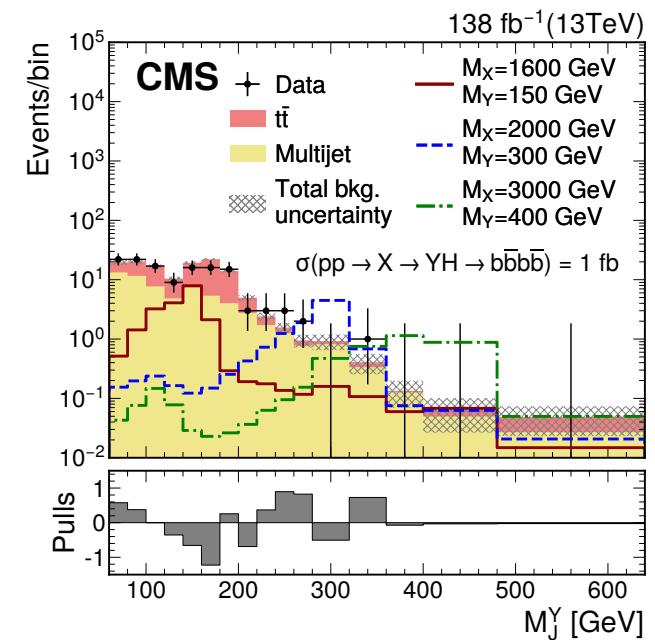
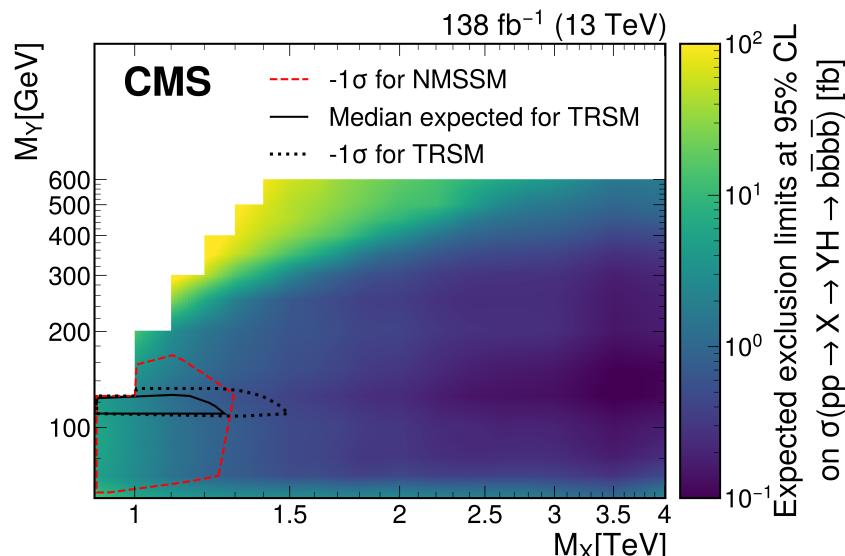
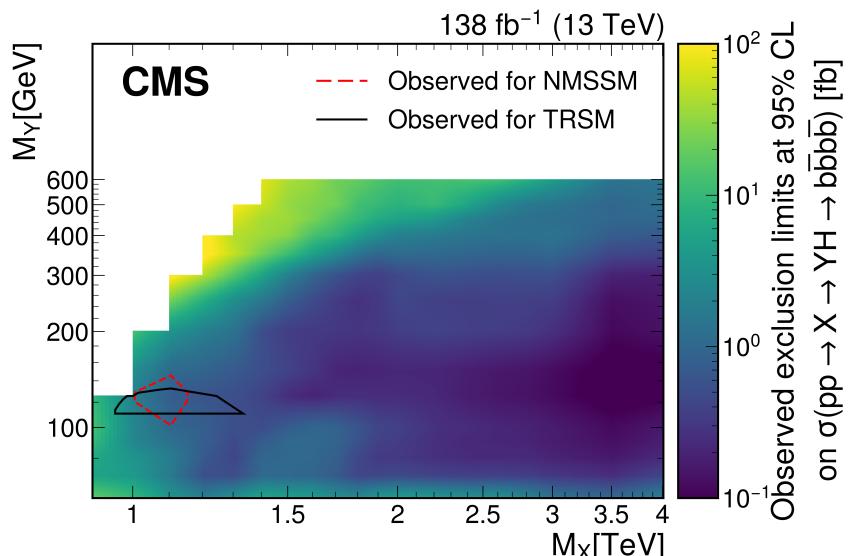
NMSSM, TRSM: $X \rightarrow YH \rightarrow b\bar{b}b\bar{b}$

arXiv:2204.12413

- Search in 0.9 - 4 TeV for X scalar and 60 - 600 GeV for Y scalar
- **Both Y and SM H are boosted**: bb pair is highly collimated
- Use **particle-net** (GNN-based algorithm) scores for H and Y jets to define SR
- Main backgrounds:
 - **Top pair** (correction from jet+lepton CR), and **QCD multi-jets** (transfer factors from CRs)
- 2D distribution M_{YJ} and M_{jj} for signal extraction

Conclusions:

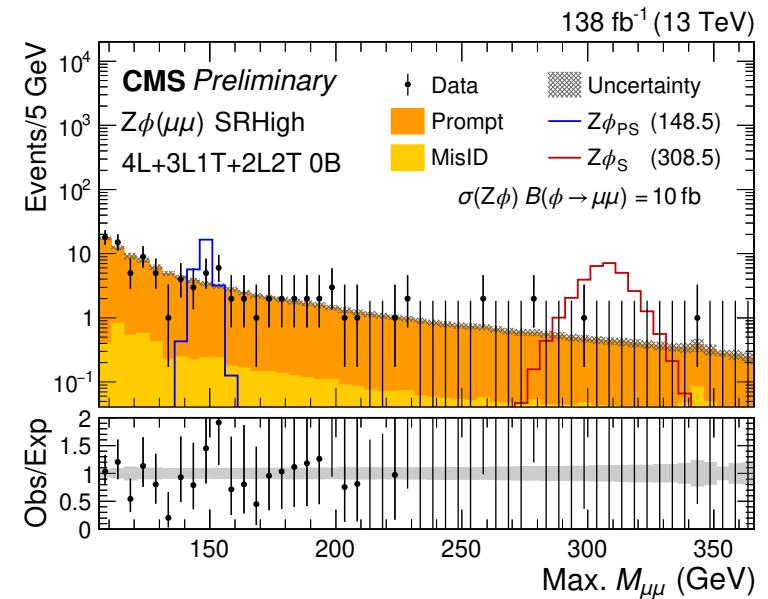
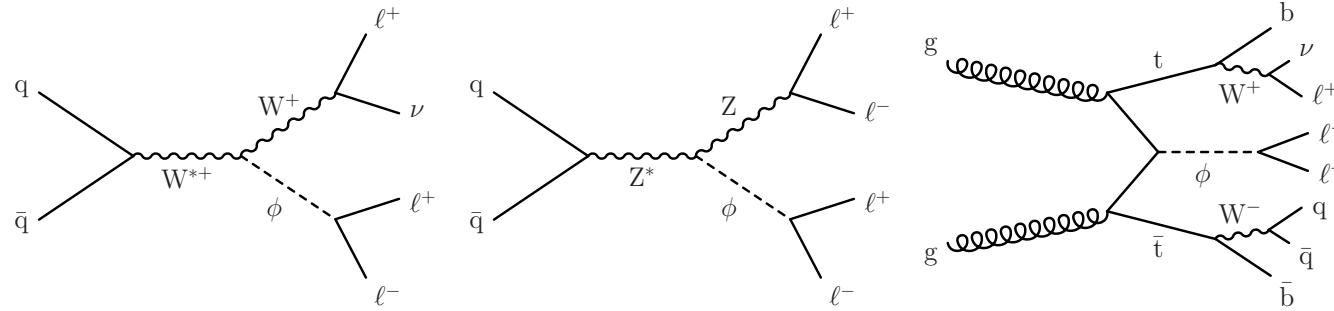
- The largest deviation from SM with local (global) significance of **$3.1 (0.7) \sigma$** found for $(m_X, m_Y) = (1600, 90)$ GeV
- NMSSM and TRSM results provided



Additional Singlet: $V\phi$, $tt\phi$, ϕ in leptonic decay channels

CMS-PAS-EXO-21-018

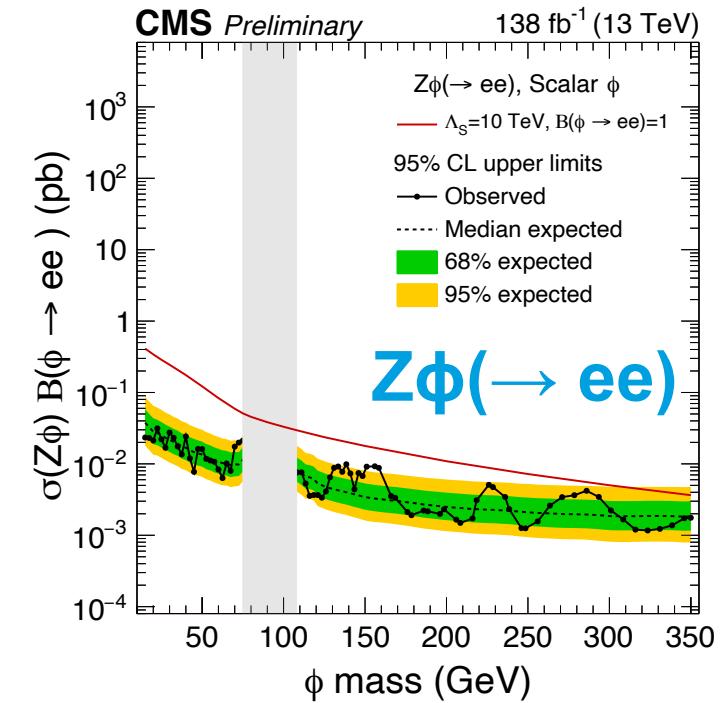
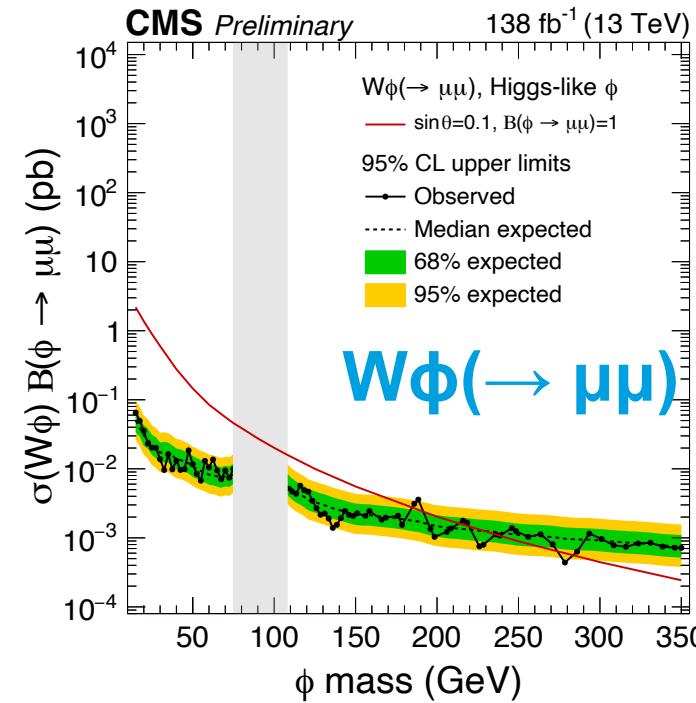
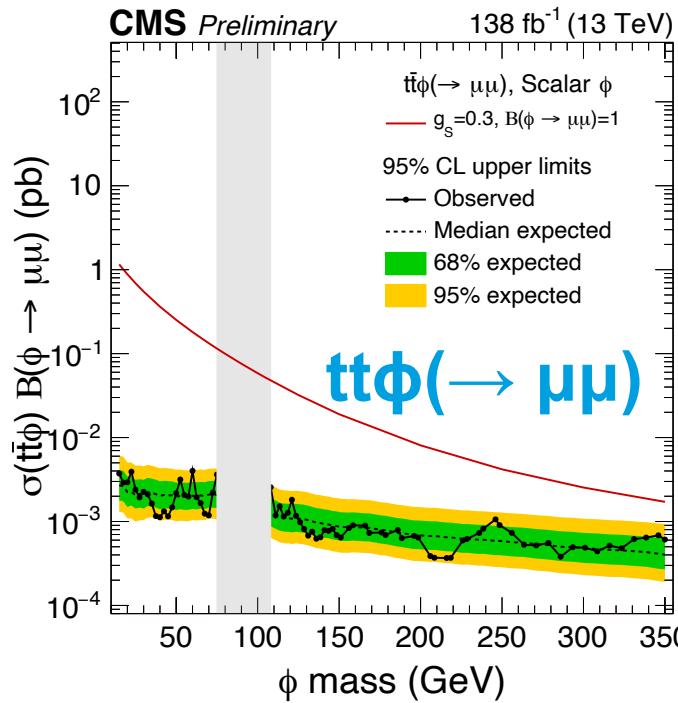
- **BSM scalar and pseudoscalar** that decay into pairs of electrons, muons, or tau leptons. Total 37 mass spectra
- Low and high ϕ mass searches for production modes: $Z\phi$, $W\phi$ and $tt\phi$
- Dominant backgrounds:
 - **Irreducible**, i.e., genuine leptons: di-boson, SM Higgs..., estimated by MC
 - **Reducible**, i.e., jet misidentified leptons, estimated by data-driven fake rate method
- Signal discriminants: **M_{Max} (M_{Min}) of di-lepton for high (low) mass search**



Additional Singlet: $V\phi$, $t\bar{t}\phi$, ϕ in leptonic decay channels

CMS-PAS-EXO-21-018

- Selective exclusion limits plots. In total, produced limits for 24 $X\phi$ signal models



- Conclusions:
 - No significant excess** has been found
 - Highest excess: 2.9 (1.4) local (global) σ significance at 156 GeV in $Z\phi(ee)$

Summary

Additional scalar boson searches in CMS

- Presented lots of interesting recent searches for additional scalar boson in CMS
- New techniques included with full 138 fb^{-1} Run 2 dataset
 - Deep Machine Learning, Particle Net...
- Covered more channels and more parameter space
- Small data excess observed but no strong deviation from SM
- Many more searches are in pipeline, and more results will be soon available
 - e.g., analysis of high resonance $\rightarrow VH$ decay (PRD 105 (2022) 032008, CMS-PAS-B2G-20-009) can be interpreted in models with additional scalars in the future
- Run 3 has just started and to deliver $> 150 \text{ fb}^{-1}$!

Stay tuned...

Thank you.



Extra contents

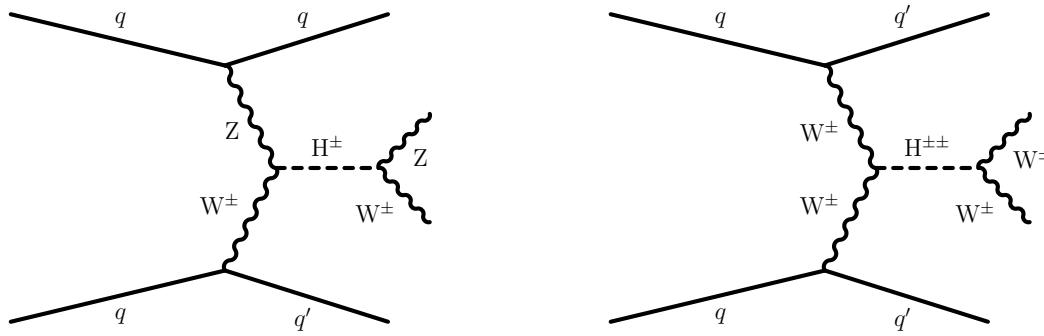
Navigations

- More CMS recent searches used full Run 2 dataset
 - CMS Charged Higgs search: $H^+ \rightarrow W^+Z$ and $H^{++} \rightarrow W^+W^+$, Eur. Phys. J. C 81 (2021) 723, on [Page 15](#)
 - CMS search: $H \rightarrow h_s h(125) \rightarrow b\bar{b}\tau\tau$, JHEP 11 (2021) 057, on [Page 17](#)
- Additional materials for:
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 - MSSM: $\phi(h, H, A) \rightarrow \tau\tau$, arXiv:2208.02717, on [Page 21](#)
 - 2HDM/MSSM: Heavy $H \rightarrow WW$, CMS-PAS-HIG-20-016, on [Page 24](#)
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CMS Charged Higgs search: $H^+ \rightarrow W^+Z$ and $H^{++} \rightarrow W^+W^+$

Eur. Phys. J. C 81 (2021) 723

- Higgs triplet model extend the sector by addition of scalar triplet
- Georgi-Machacek (GM) model adds one real & one complex SU(2) triplet
- Appearance of the H^+W^+Z coupling at tree-level and presence of doubly-charged Higgs bosons H^{++}

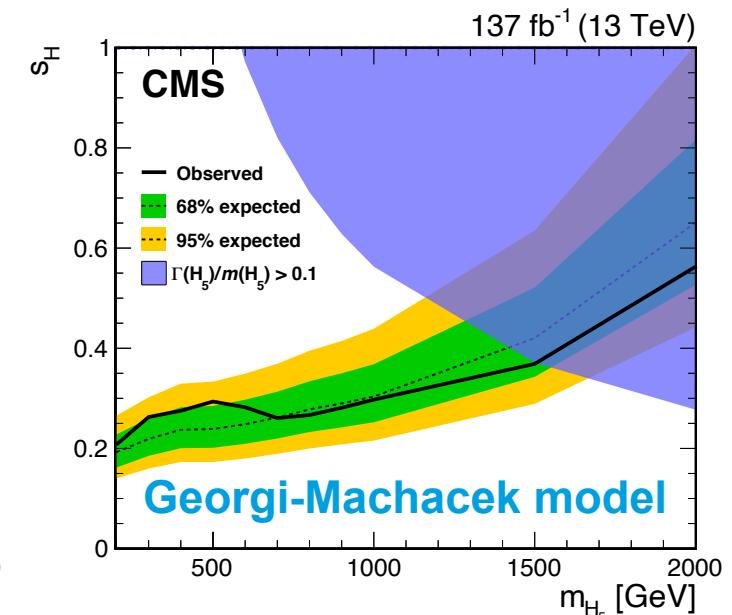
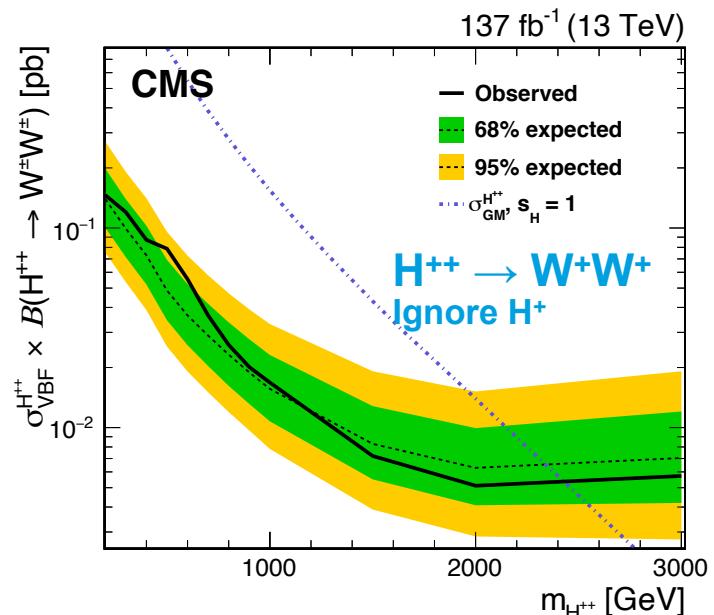
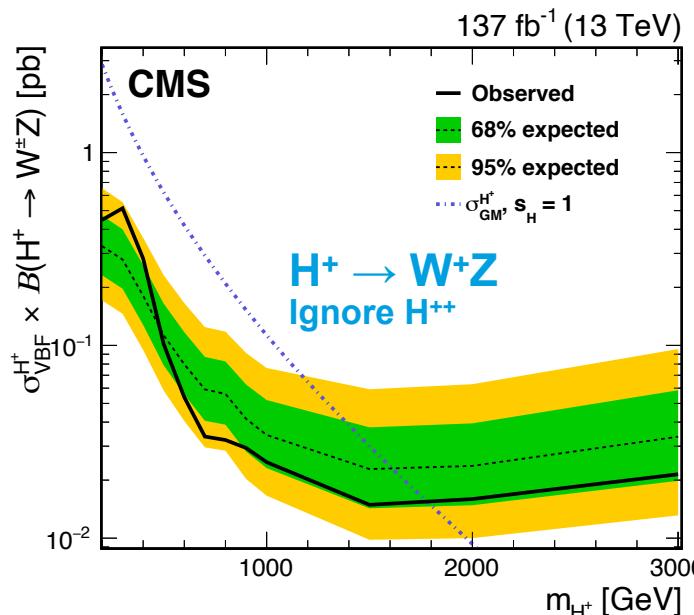
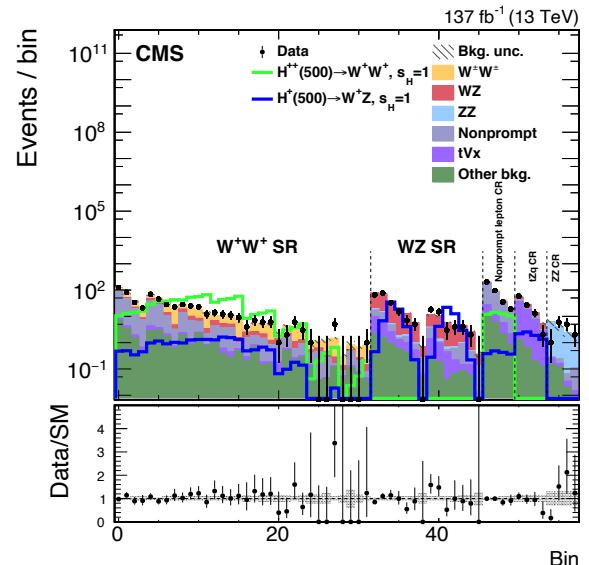


- Multi-lepton + jets + missing transverse energy final state
- Backgrounds:
 - Irreducible: SM di-boson (CR validated) and tZq (from MC)
 - Reducible: Misidentified lepton, estimated from data-driven in CR

CMS Charged Higgs search: $H^+ \rightarrow W^+Z$ and $H^{++} \rightarrow W^+W^+$

Eur. Phys. J. C 81 (2021) 723

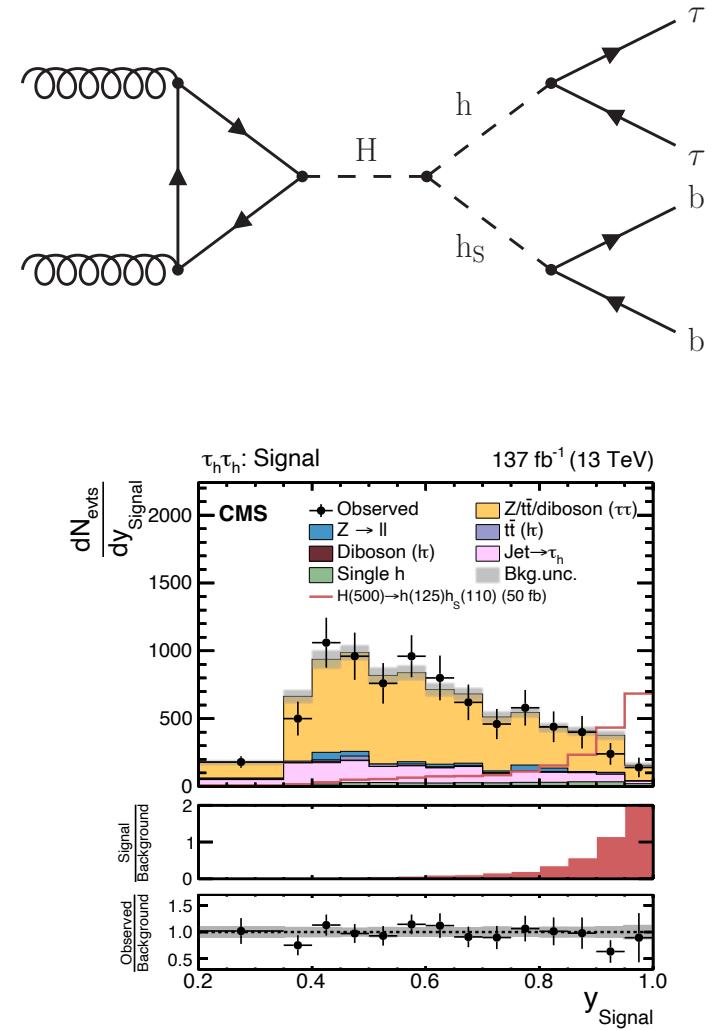
- Using 2D distributions of M_{jj} and transverse mass M_{VV}^T to extract signals
- Excluded $s_H > 0.20\text{--}0.35$ for $m_{H_5} = 0.2\text{--}1.5$ TeV in GM model
- Improved limits w.r.t previous CMS results
- Theoretically inaccessible ($\Gamma_{H_5} > 0.1m_{H_5}$)



CMS search: $H \rightarrow h_s h(125) \rightarrow bb\tau\tau$

JHEP 11 (2021) 057

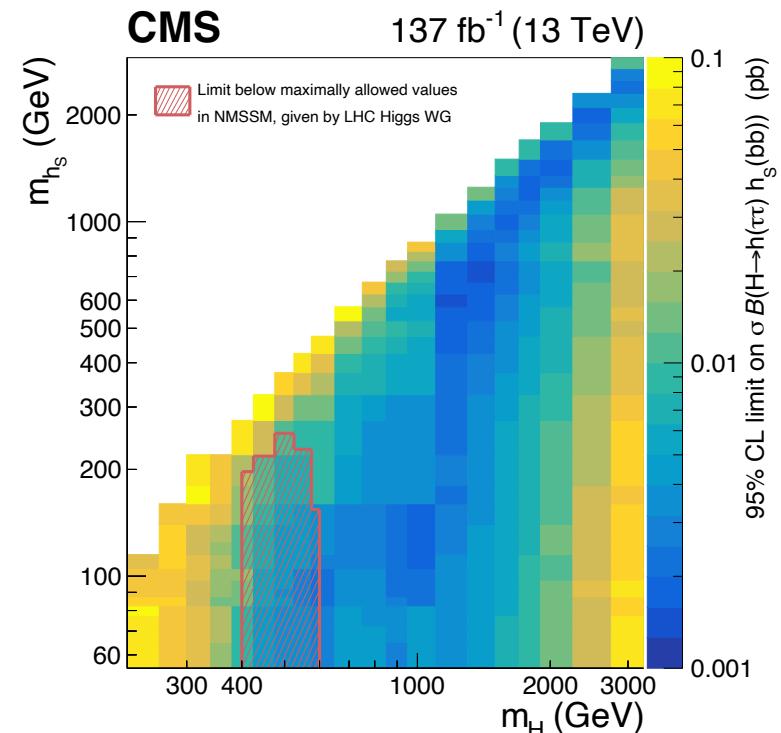
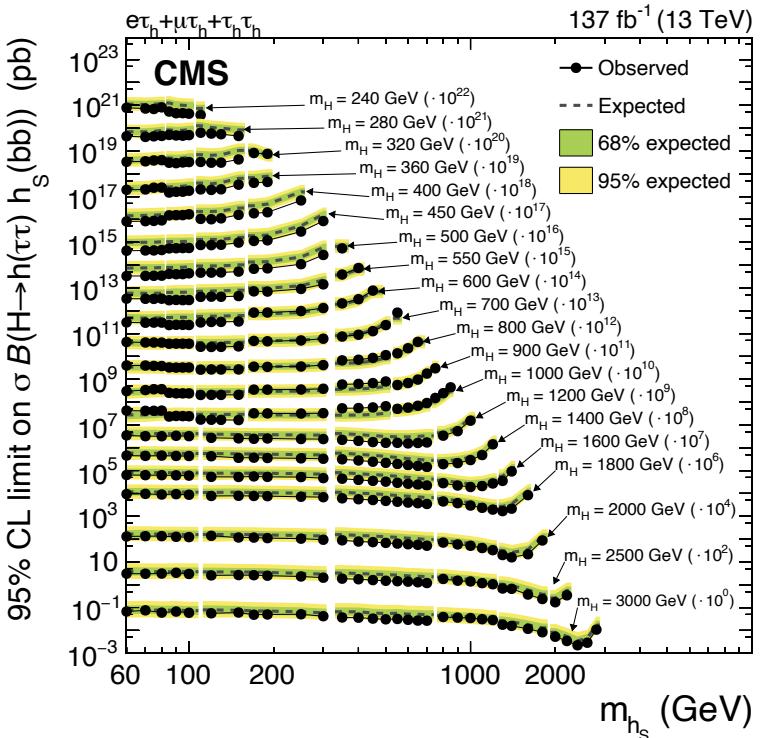
- In NMSSM model, H is a heavy Higgs, h is the SM Higgs, and h_s another additional Higgs
- Three decay channels of $\tau\tau$: $e\tau_h$, $\mu\tau_h$ and $\tau_h\tau_h$ and require ≥ 2 jets and ≥ 1 b-jet
- Dominant backgrounds:
 - Genuine tau pairs, estimated from τ embedding technique
 - Misidentified τ_h : fake factor method, data-driven
 - 94% of background events estimated from data
- Each NN has 5 scores as outputs: tau pairs, top pair, jet $\rightarrow \tau_h$, misc., and signal
 - Use NN score in signal category as signal discriminant:
 - 1 NN trained for similar mass hypothesis \sim total 68 training



CMS search: $H \rightarrow h_s h(125) \rightarrow bb\tau\tau$

JHEP 11 (2021) 057

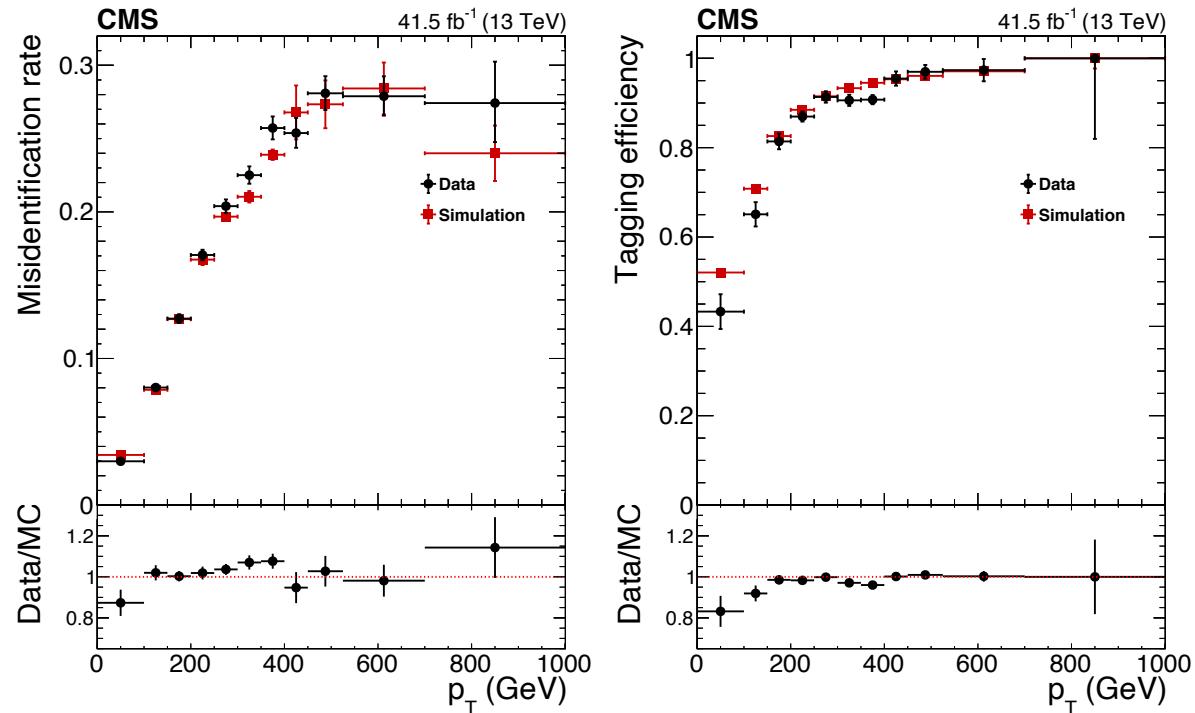
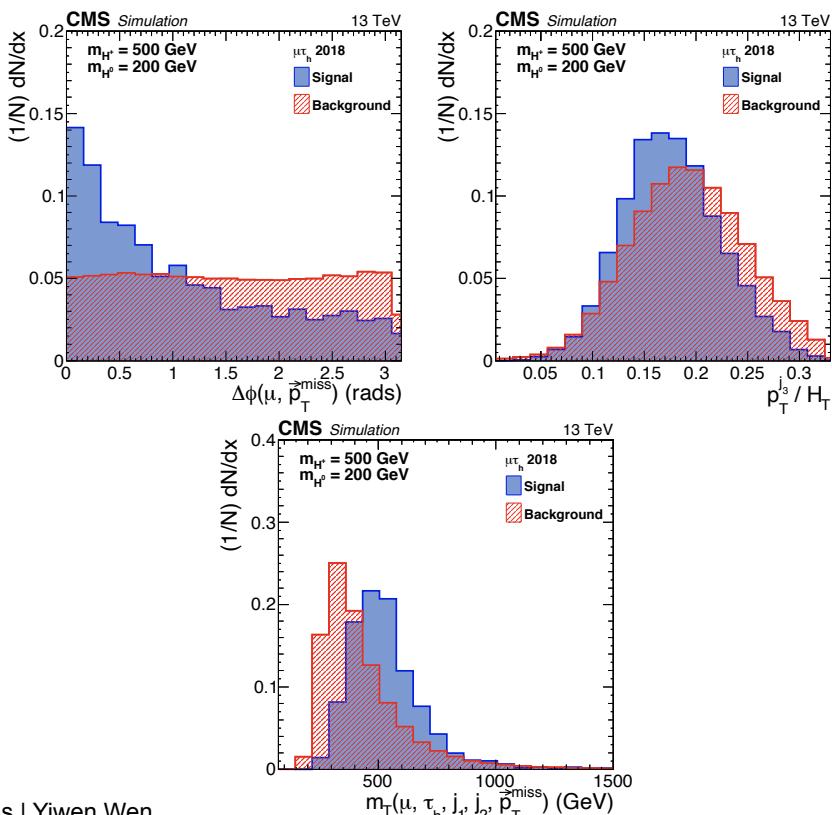
- limits are derived as a function of m_H and m_{h_s}
- All upper limits shown in a single figure by scaling values by orders of 10
- Upper limits of 125 - 2.7 fb for $m_H = 240 - 1000$ GeV ($m_{h_s} = 85-250$ GeV)
- NMSSM constrained for $400 \leq m_H \leq 600$ GeV and $60 \leq m_{h_s} \leq 200$ GeV



2HDM: $H^+ \rightarrow H W^+$

Additional materials

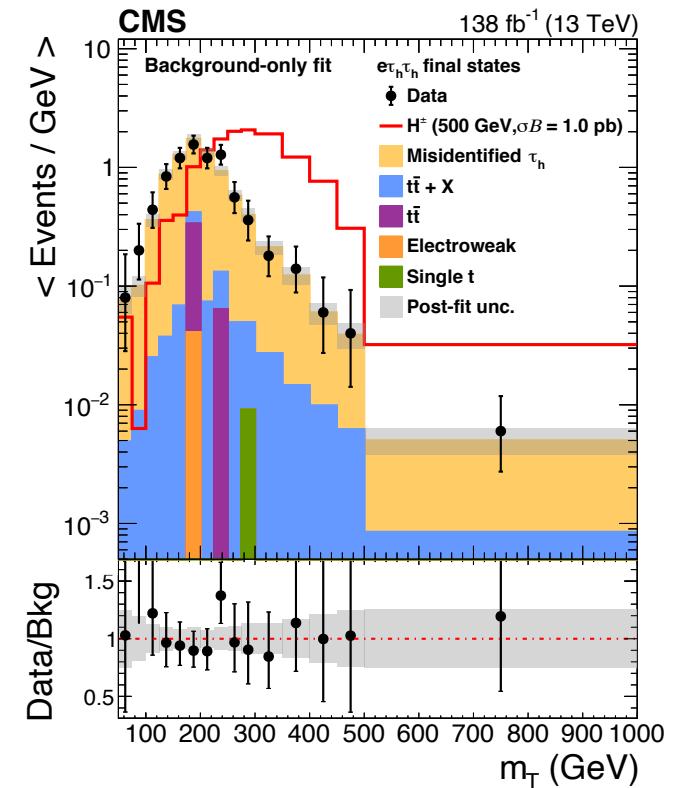
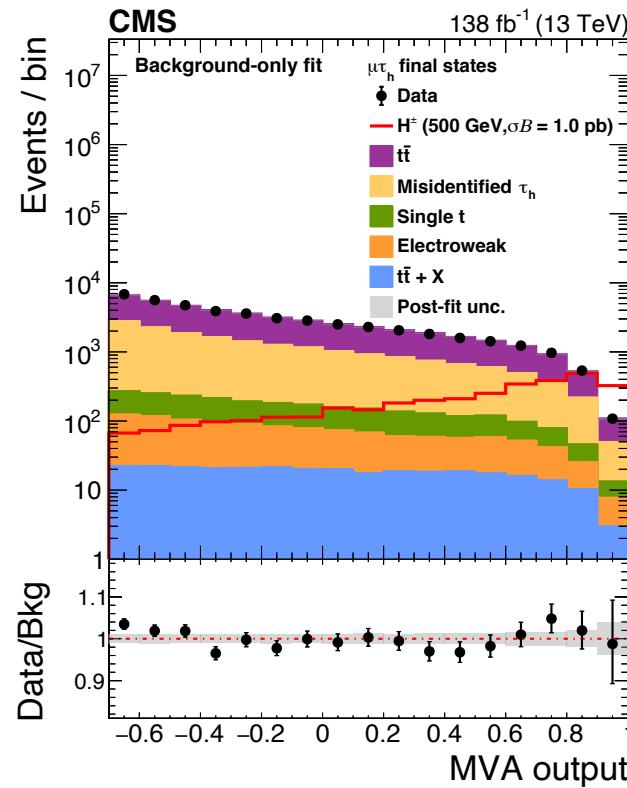
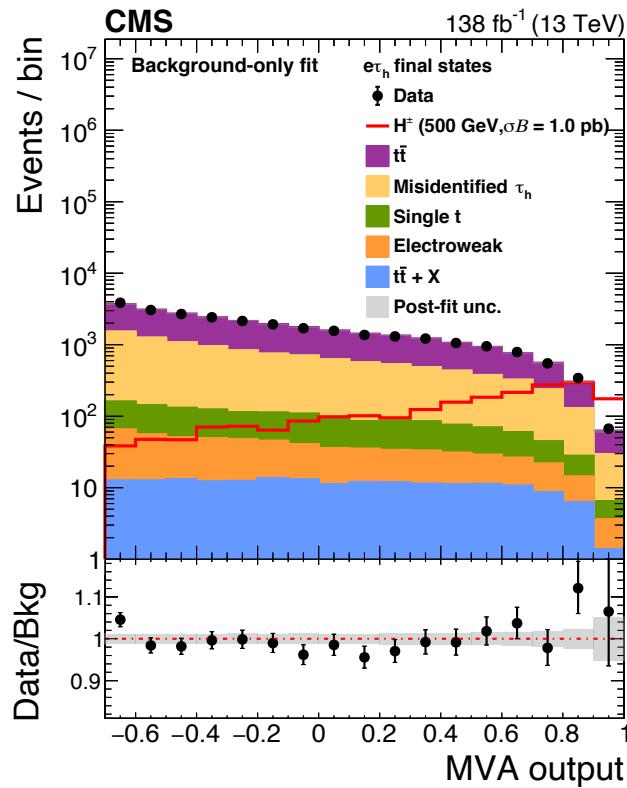
- Top tagger efficiencies for Loose working point
 - ~27% misidentification rate and 95% efficiency for plateau $p_T > 350$ GeV
- BDT input variables for $e\tau_h$, $\mu\tau_h$ channels



2HDM: $H^+ \rightarrow H W^+$

Additional materials

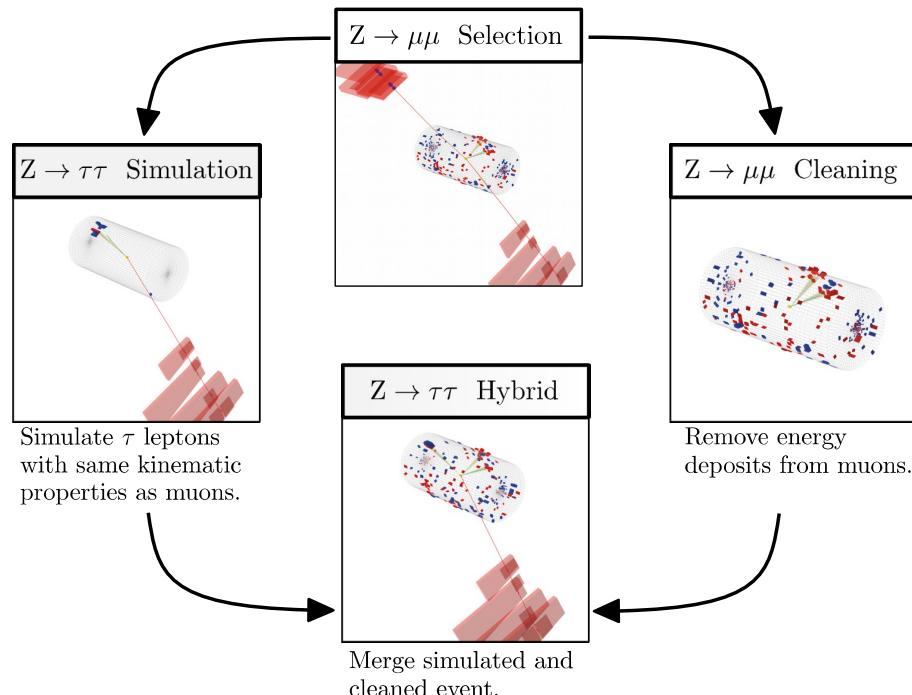
- BDT scores for $e\tau_h$, $\mu\tau_h$ channels and transverse mass distribution for $e\tau_h\tau_h$ channel



MSSM: $\phi(h, H, A) \rightarrow \tau\tau$

Additional materials

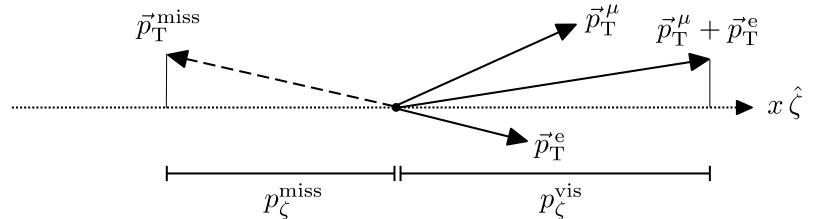
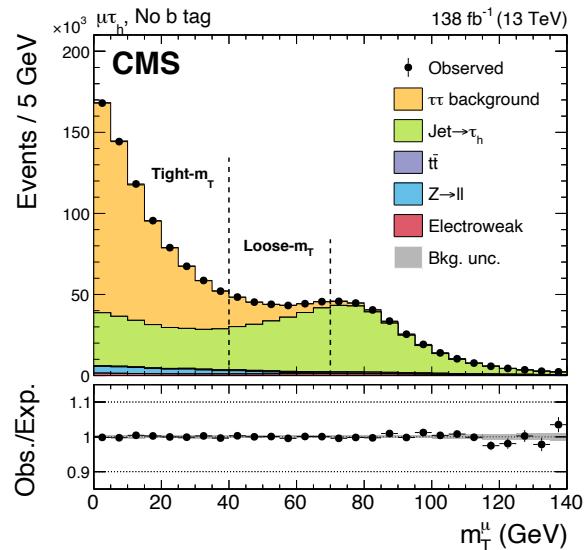
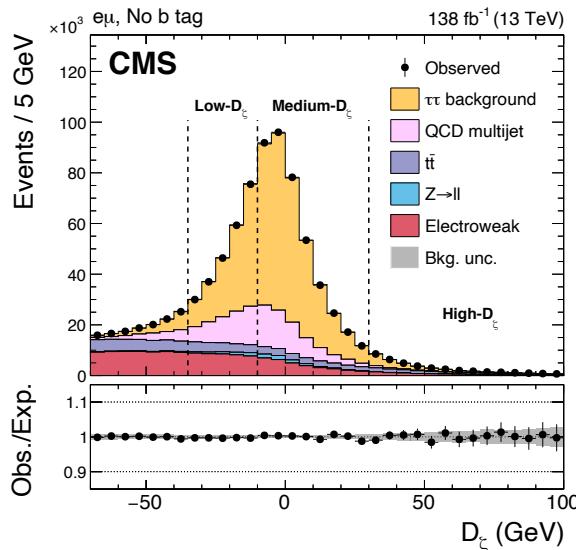
- τ embedding technique: Create hybrid event with minimum simulation needed
 - Select $Z \rightarrow \mu\mu$ events in observed data
 - Clean all μ -related energy deposits
 - Simulate $\tau\tau$ events with same kinematic properties as muons
 - Merged μ -removed $Z \rightarrow \mu\mu$ with simulated $Z \rightarrow \tau\tau$ to get hybrid event



MSSM: $\phi(h, H, A) \rightarrow \tau\tau$

Additional materials

- Event categories building to target different kinematics



High mass > 250
GeV search:

No b tag			b tag			
eμ	Low- D_ζ	Medium- D_ζ	High- D_ζ	Low- D_ζ	Medium- D_ζ	High- D_ζ
eτ _h	Loose- m_T		Tight- m_T	Loose- m_T		Tight- m_T
μτ _h	Loose- m_T		Tight- m_T	Loose- m_T		Tight- m_T
τ _h τ _h						
t̄(eμ)						$D_\zeta < -35 \text{ GeV}$

Legend: Signal region (SR) (white), Control region (dark blue).

Low mass < 250 GeV
search:

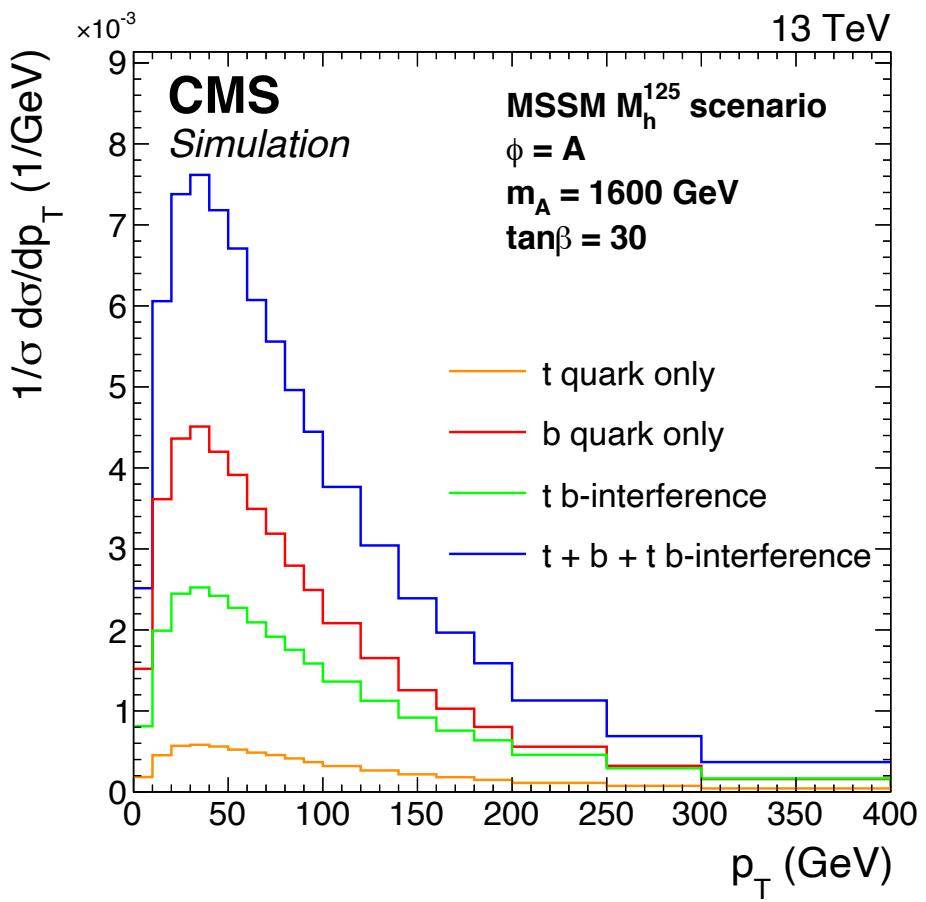
No b tag			b tag	
eμ	Medium- D_ζ	High- D_ζ	$p_T^{\tau\tau} < 50 \text{ GeV}$	$p_T^{\tau\tau} < 50 \text{ GeV}$
			$50 < p_T^{\tau\tau} < 100 \text{ GeV}$	$50 < p_T^{\tau\tau} < 100 \text{ GeV}$
			$100 < p_T^{\tau\tau} < 200 \text{ GeV}$	$100 < p_T^{\tau\tau} < 200 \text{ GeV}$
			$p_T^{\tau\tau} > 200 \text{ GeV}$	$p_T^{\tau\tau} > 200 \text{ GeV}$
eτ _h	Tight- m_T		$p_T^{\tau\tau} < 50 \text{ GeV}$	$p_T^{\tau\tau} < 50 \text{ GeV}$
			$50 < p_T^{\tau\tau} < 100 \text{ GeV}$	$50 < p_T^{\tau\tau} < 100 \text{ GeV}$
			$100 < p_T^{\tau\tau} < 200 \text{ GeV}$	$100 < p_T^{\tau\tau} < 200 \text{ GeV}$
			$p_T^{\tau\tau} > 200 \text{ GeV}$	$p_T^{\tau\tau} > 200 \text{ GeV}$
μτ _h	Tight- m_T		$p_T^{\tau\tau} < 50 \text{ GeV}$	$p_T^{\tau\tau} < 50 \text{ GeV}$
			$50 < p_T^{\tau\tau} < 100 \text{ GeV}$	$50 < p_T^{\tau\tau} < 100 \text{ GeV}$
			$100 < p_T^{\tau\tau} < 200 \text{ GeV}$	$100 < p_T^{\tau\tau} < 200 \text{ GeV}$
			$p_T^{\tau\tau} > 200 \text{ GeV}$	$p_T^{\tau\tau} > 200 \text{ GeV}$
τ _h τ _h			$p_T^{\tau\tau} < 50 \text{ GeV}$	$p_T^{\tau\tau} < 50 \text{ GeV}$
			$50 < p_T^{\tau\tau} < 100 \text{ GeV}$	$50 < p_T^{\tau\tau} < 100 \text{ GeV}$
			$100 < p_T^{\tau\tau} < 200 \text{ GeV}$	$100 < p_T^{\tau\tau} < 200 \text{ GeV}$
			$p_T^{\tau\tau} > 200 \text{ GeV}$	$p_T^{\tau\tau} > 200 \text{ GeV}$
t̄(eμ)				$D_\zeta < -35 \text{ GeV}$

Legend: Signal region (SR) (white), Control region (dark blue).

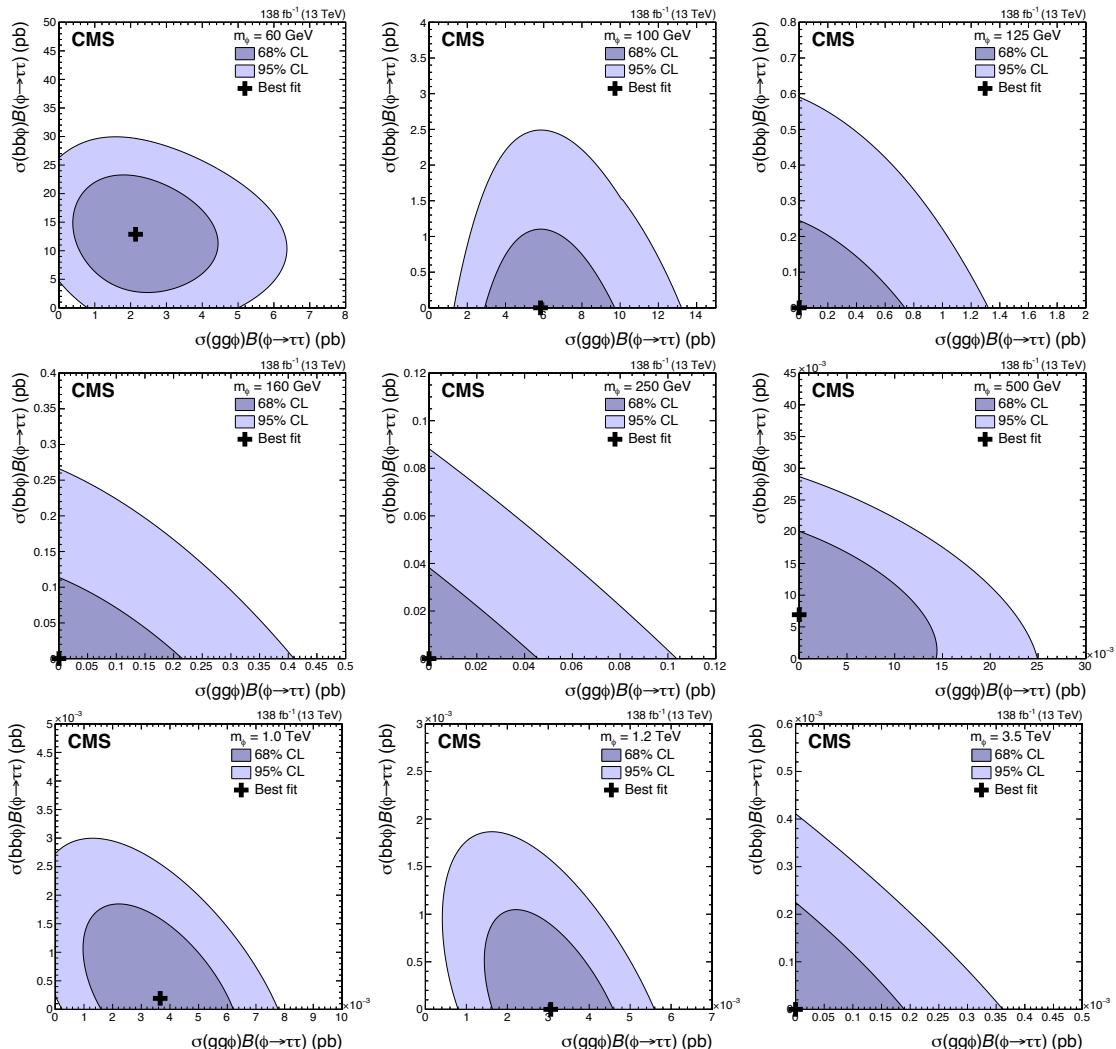
MSSM: $\phi(h, H, A) \rightarrow \tau\tau$

Additional materials

- Composition of signals for MSSM benchmark m^h_{125}



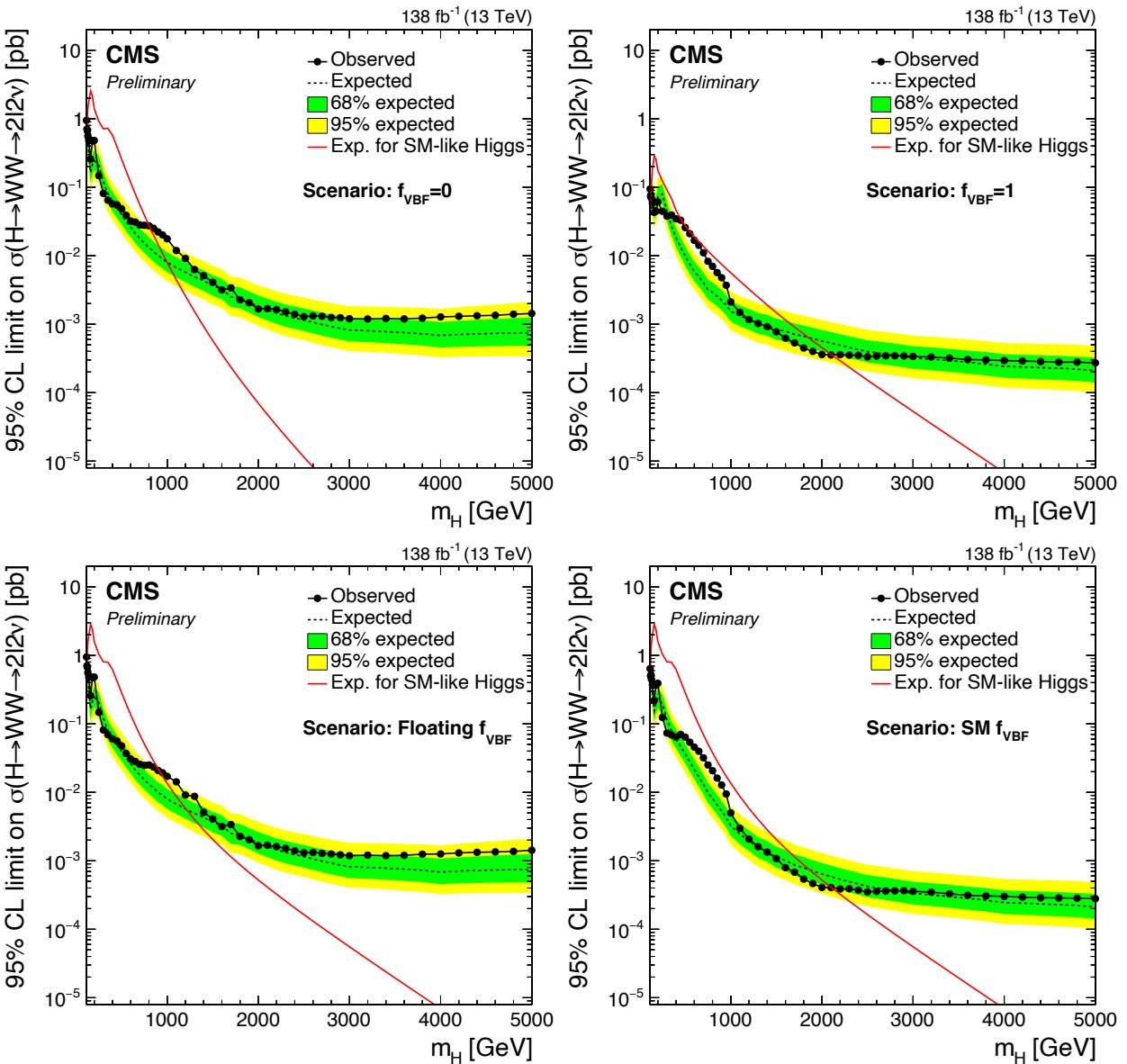
- 2D Likelihood scans for $bb\phi$ and $gg\phi$ cross section.
SM expectation is (0,0)



2HDM/MSSM: heavy $H \rightarrow WW$

Additional materials

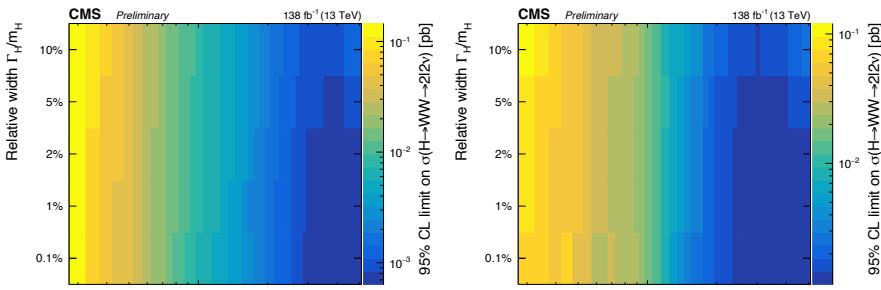
- Exclusion Limits for 4 VBF relative contribution scenarios



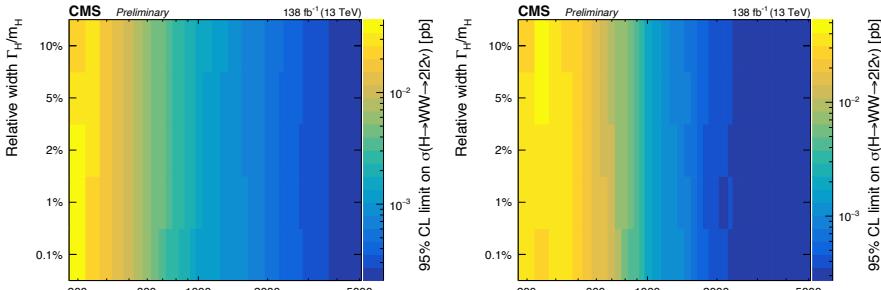
2HDM/MSSM: heavy $H \rightarrow WW$

Additional materials

$f_{VBF} = 0:$

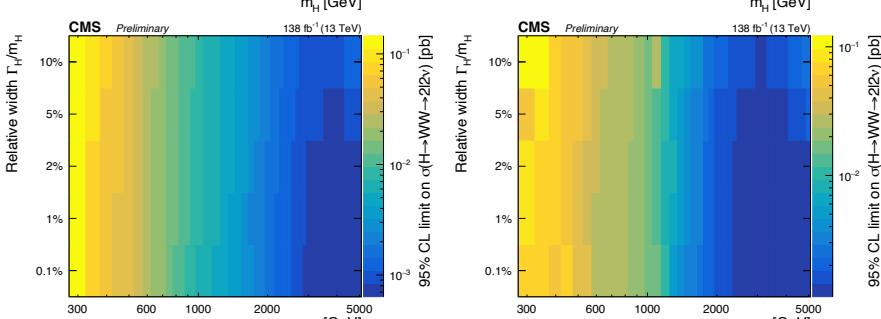


$f_{VBF} = 1:$

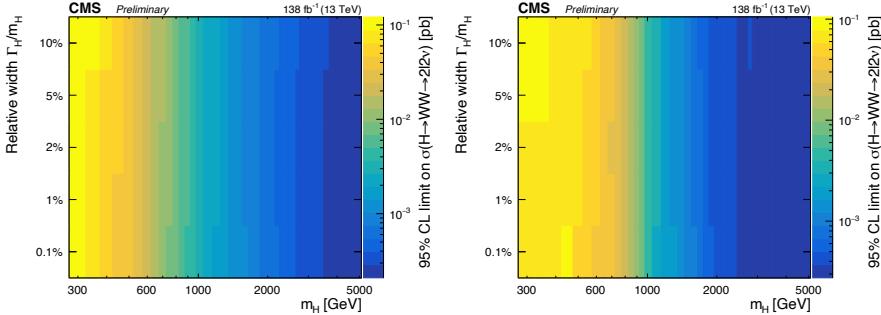


- Exclusion Limits signal mass and width for 4 VBF relative contribution scenarios

Floatting $f_{VBF}:$



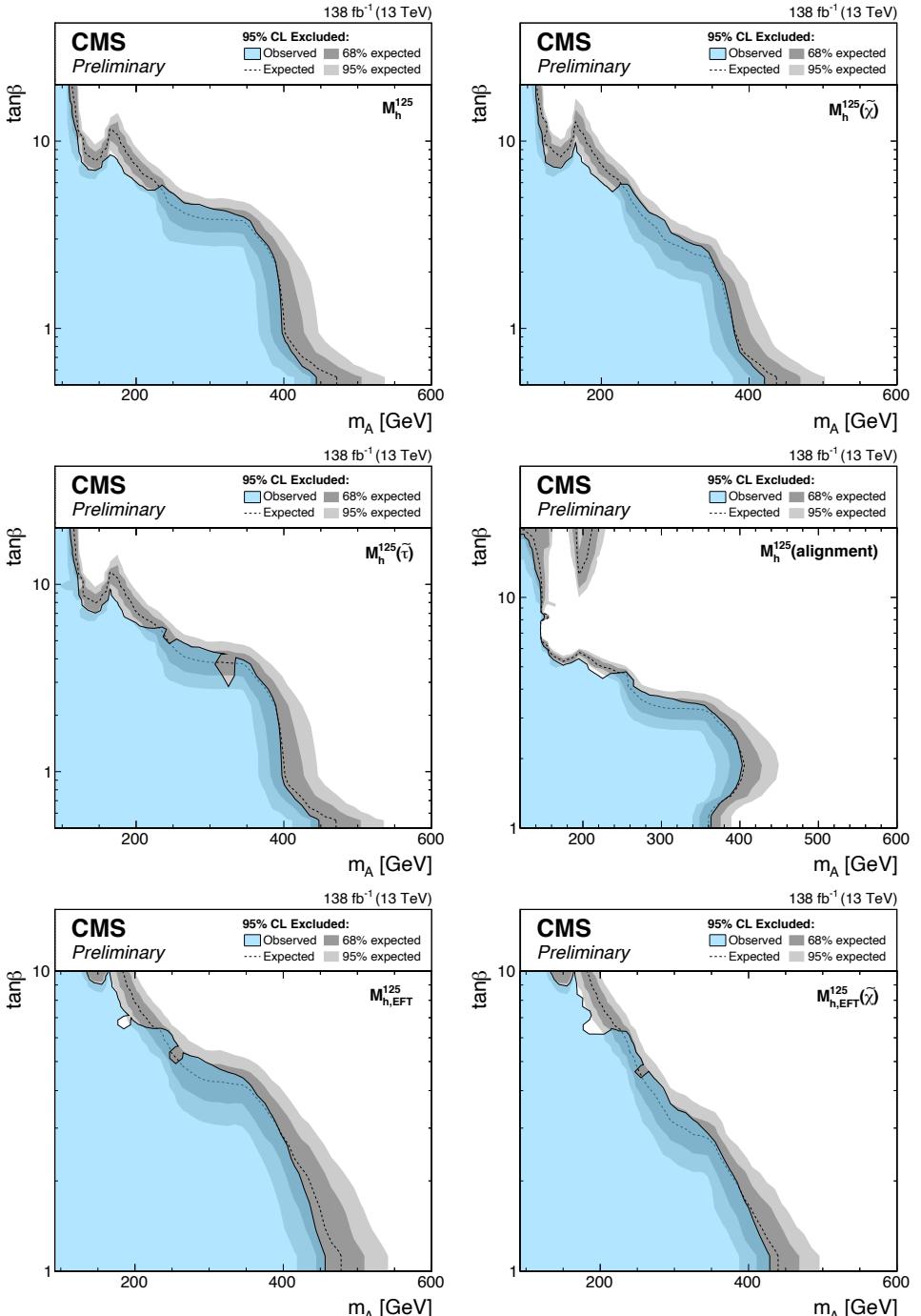
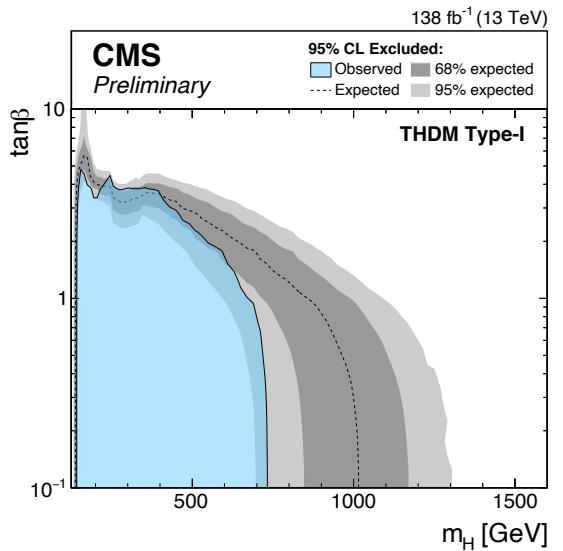
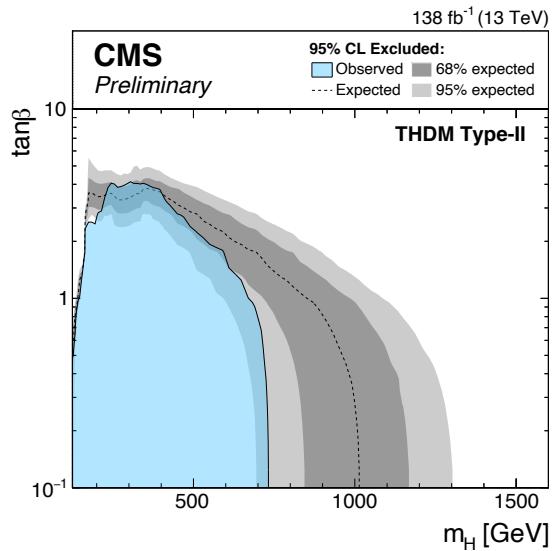
SM-like $f_{VBF}:$



2HDM/MSSM: heavy $H \rightarrow WW$

Additional materials

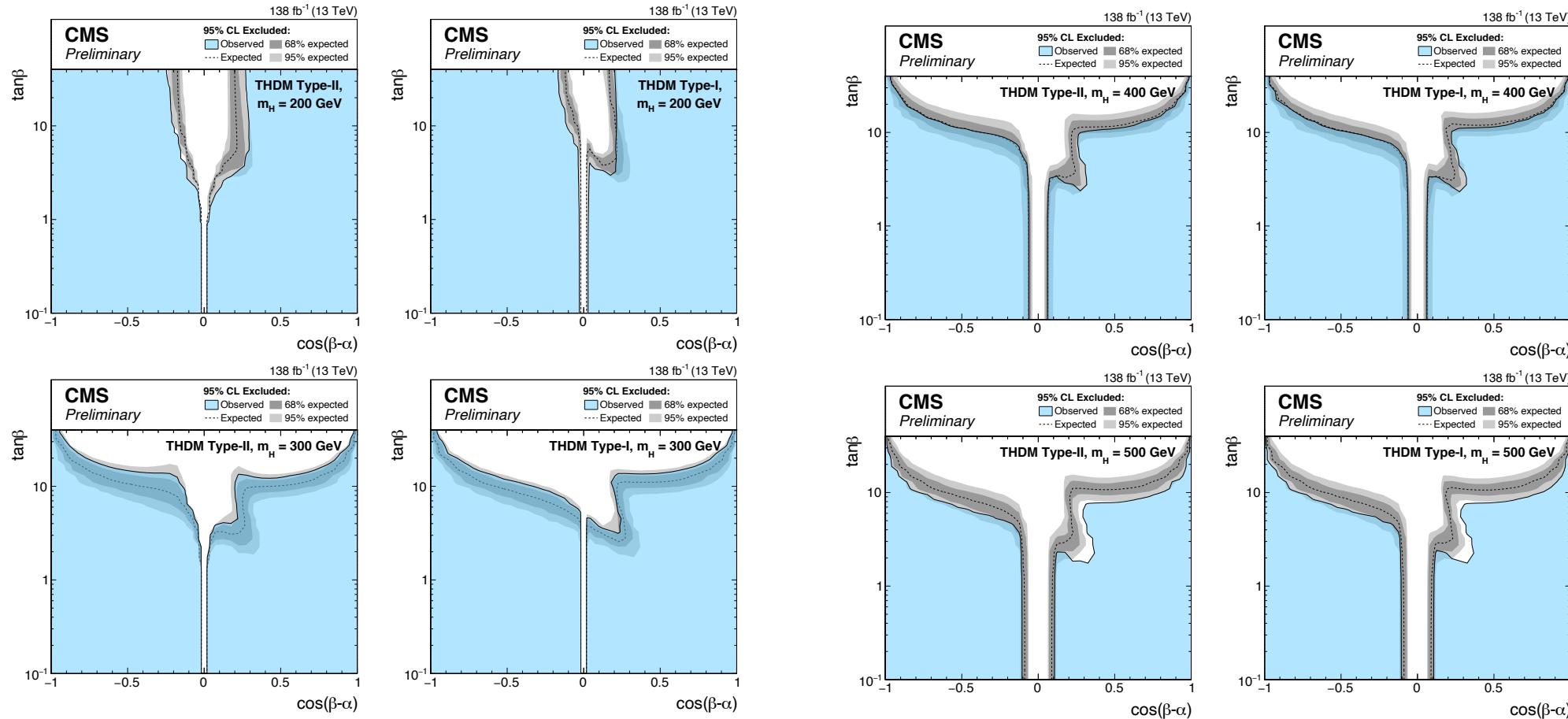
- Exclusion Limits different MSSM benchmark scenarios
- And 2HDM Type-I and Type-II



2HDM/MSSM: heavy $H \rightarrow WW$

Additional materials

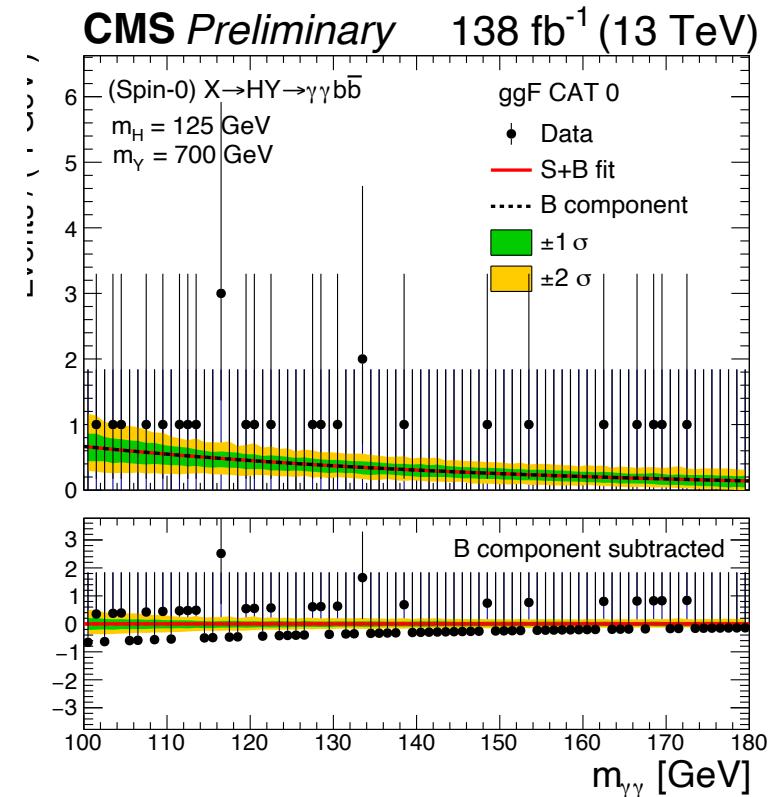
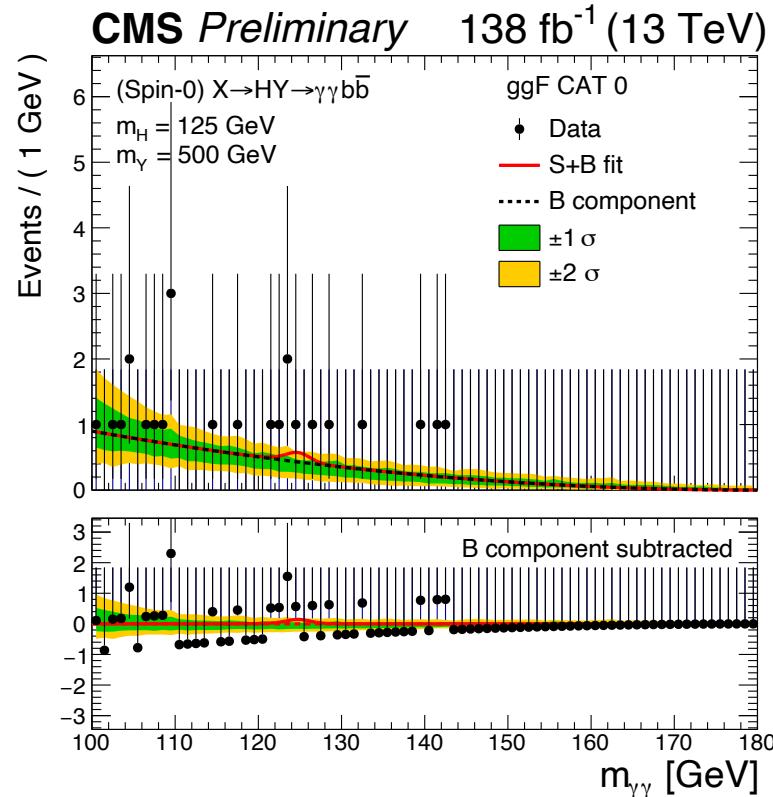
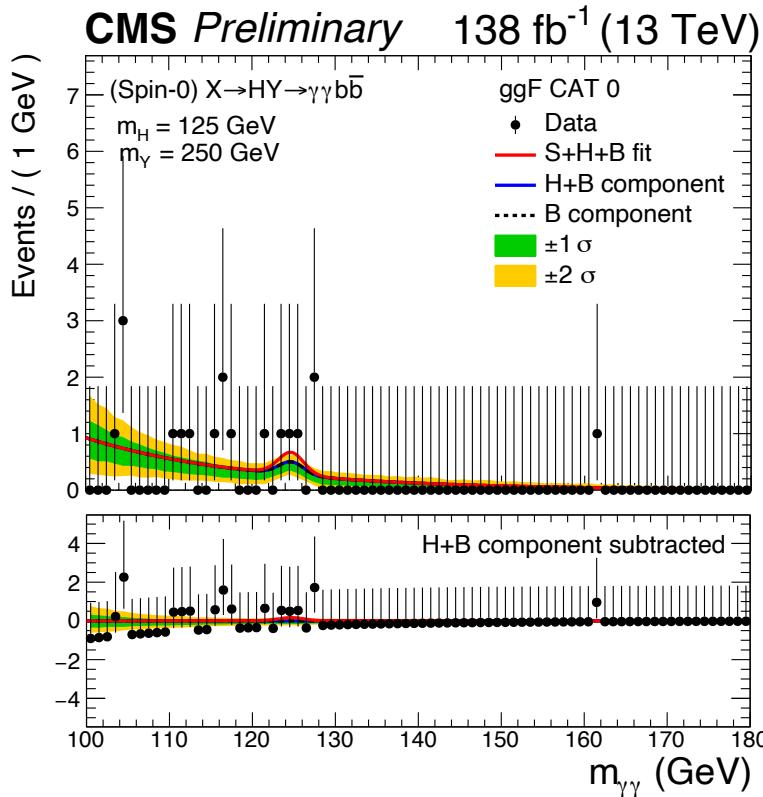
- Exclusion limits in 2HDM Type-I and Type-II parameter space for different mass points



NMSSM, TRSM: $X \rightarrow YH \rightarrow bb\gamma\gamma$

Additional materials

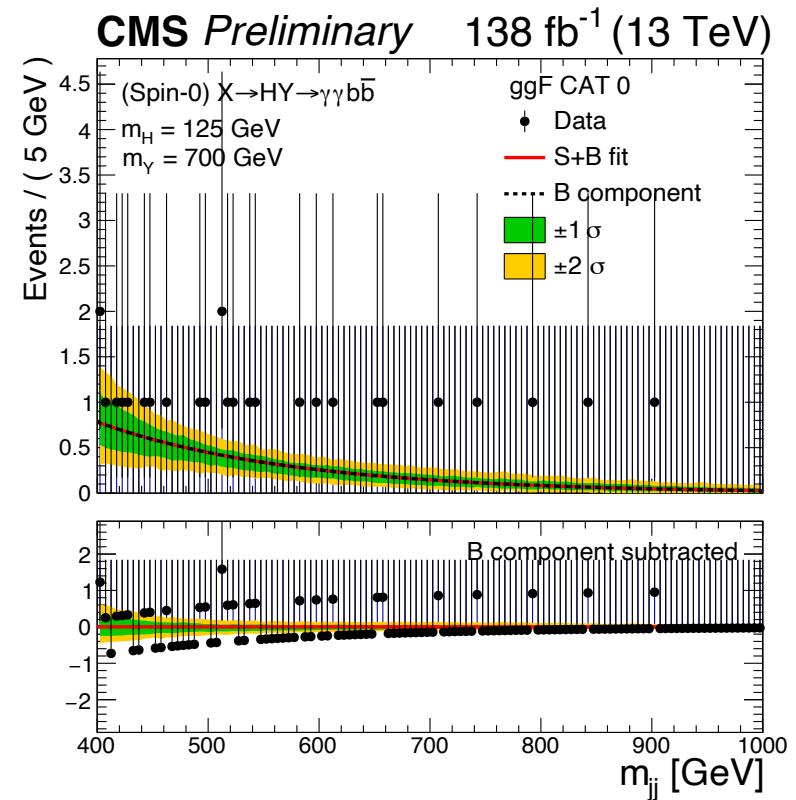
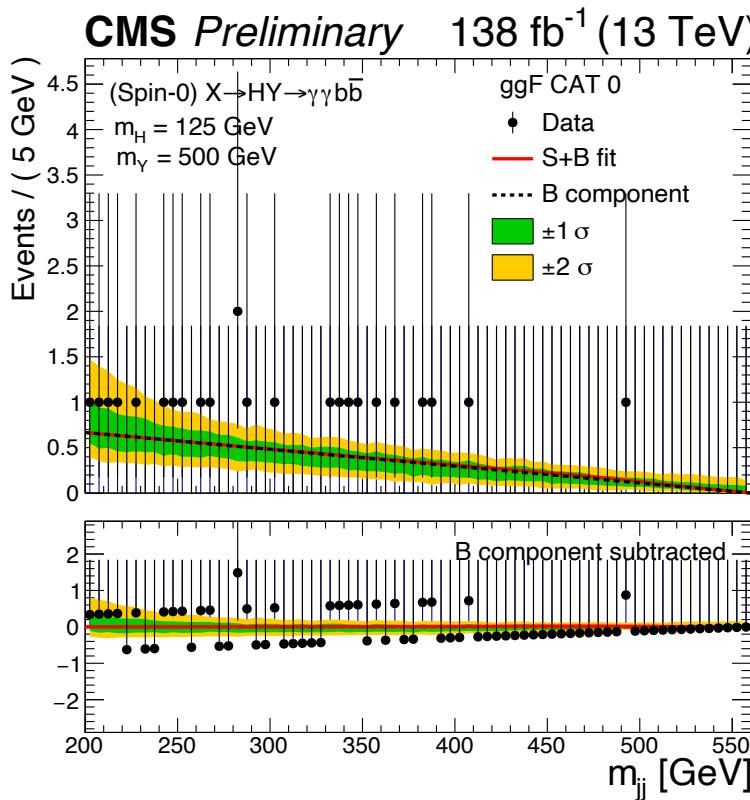
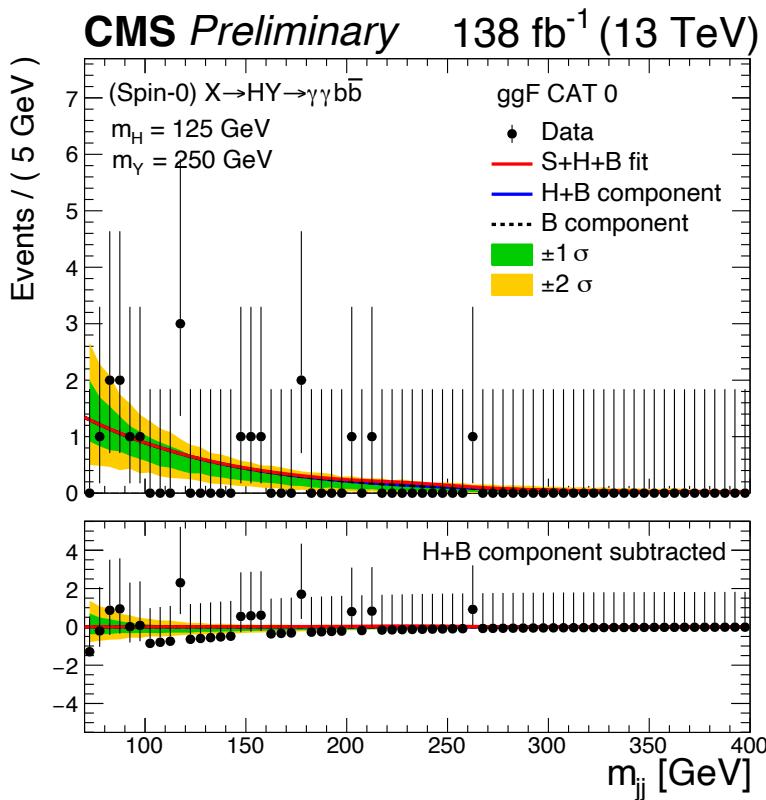
- $m_{\gamma\gamma}$ distributions



NMSSM, TRSM: $X \rightarrow YH \rightarrow bb\gamma\gamma$

Additional materials

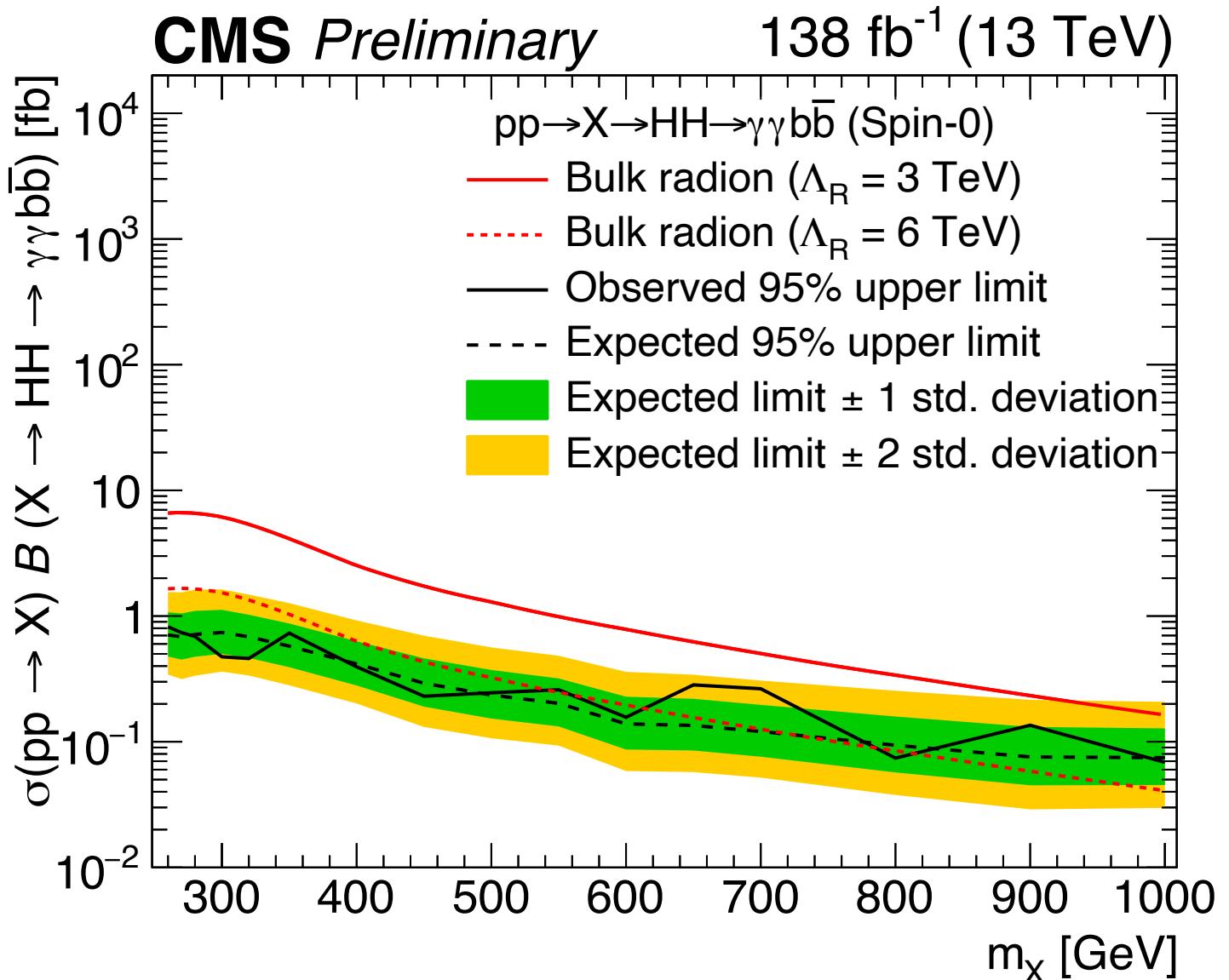
- m_{jj} distributions



NMSSM, TRSM: $X \rightarrow HH \rightarrow bb\gamma\gamma$

Additional materials

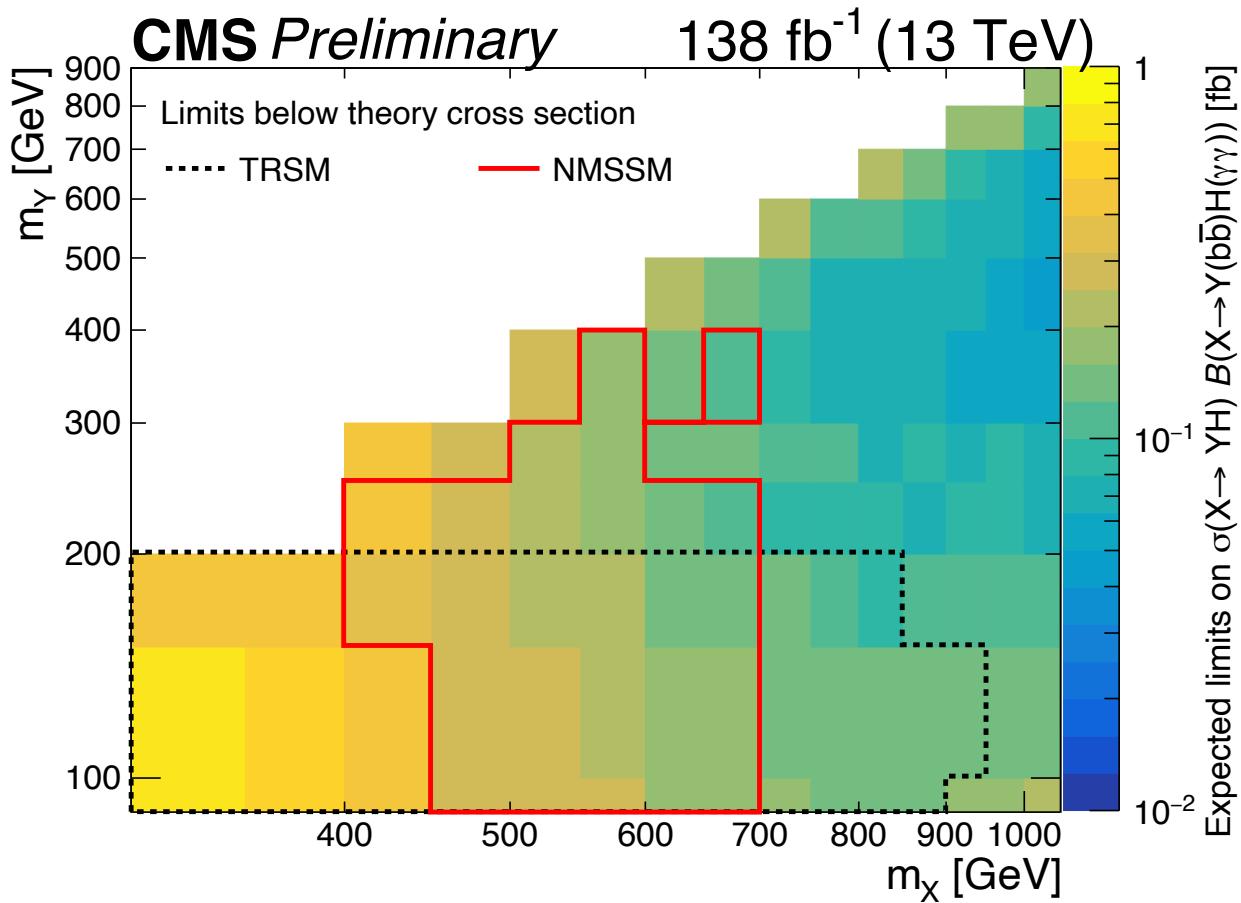
- Limits



NMSSM, TRSM: $X \rightarrow YH \rightarrow b\bar{b}\gamma\gamma$

Additional materials

- Expected NMSSM and TRSM limits

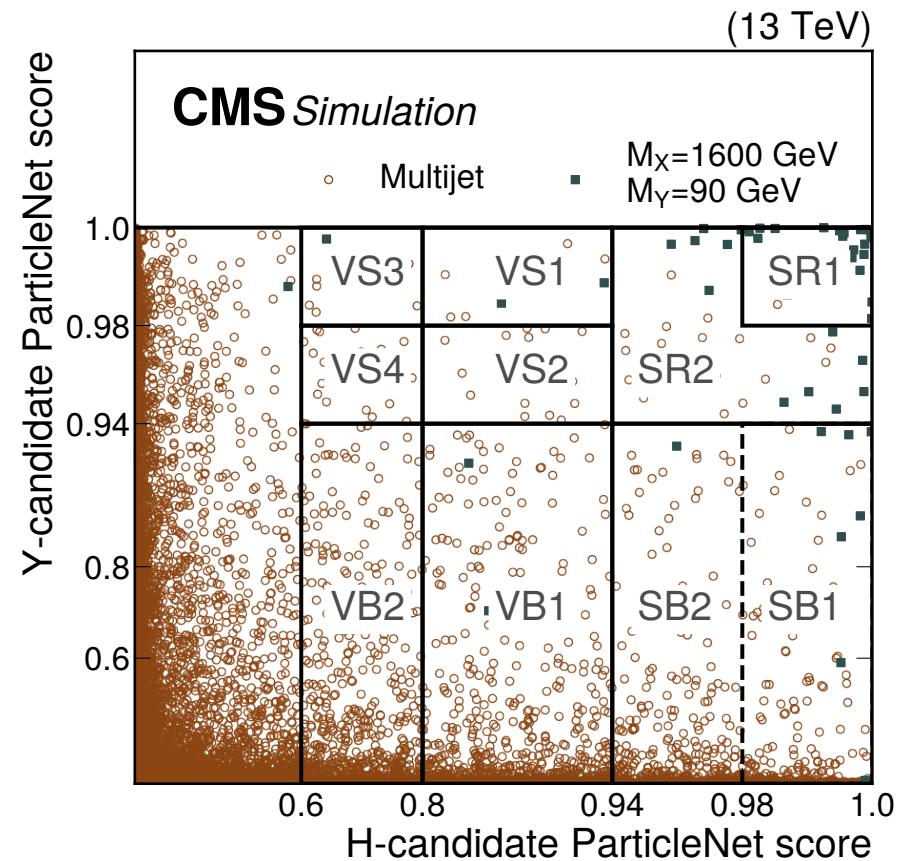


NMSSM, TRSM: $X \rightarrow YH \rightarrow bbbb$

Additional materials

- ParticleNet categorization

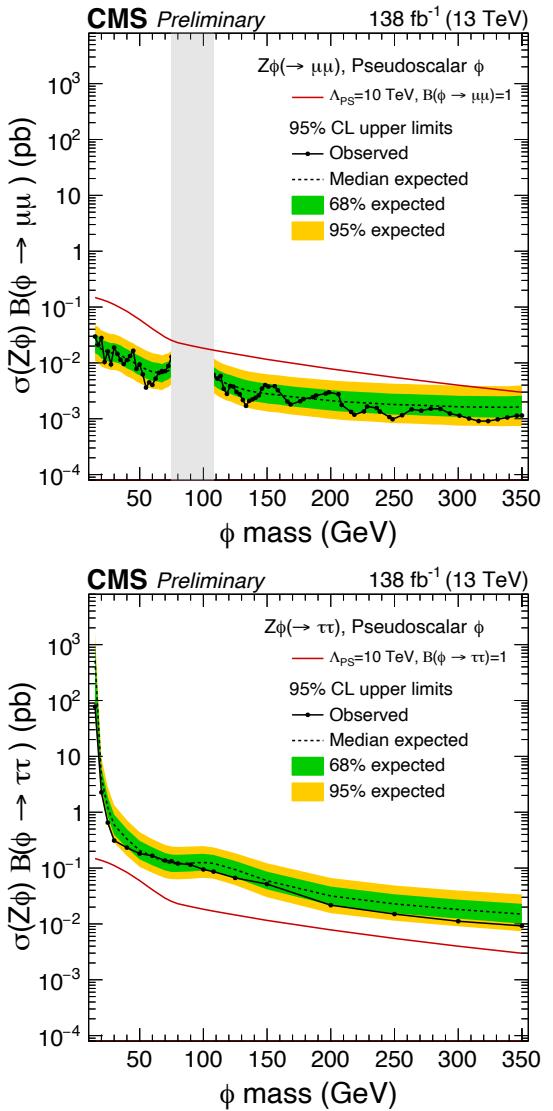
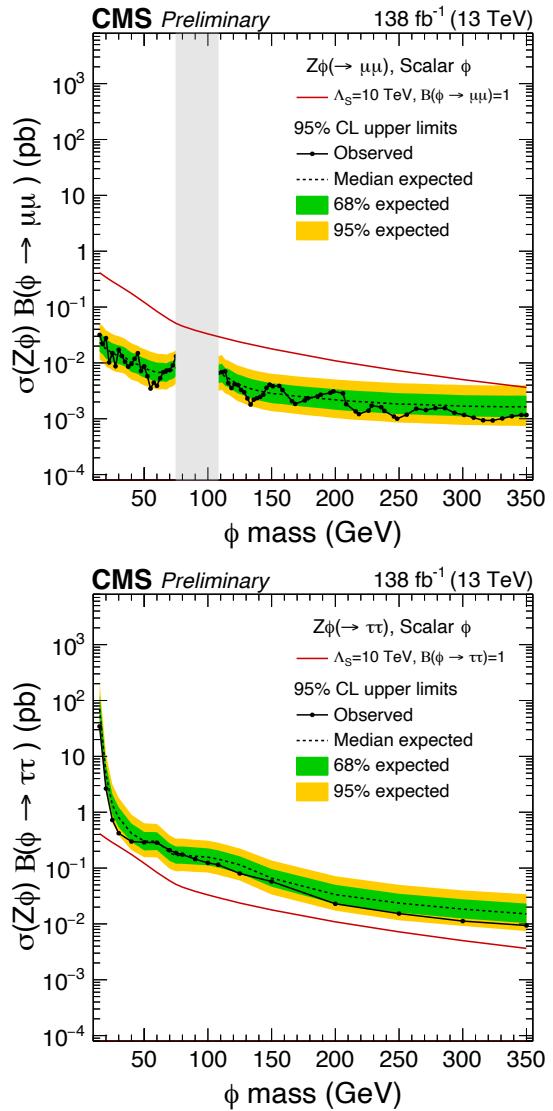
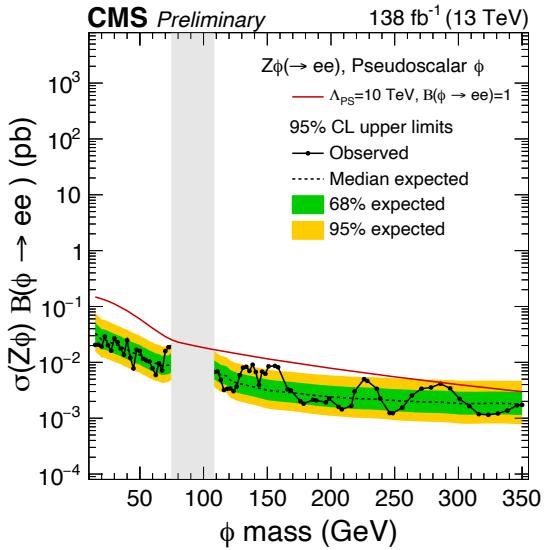
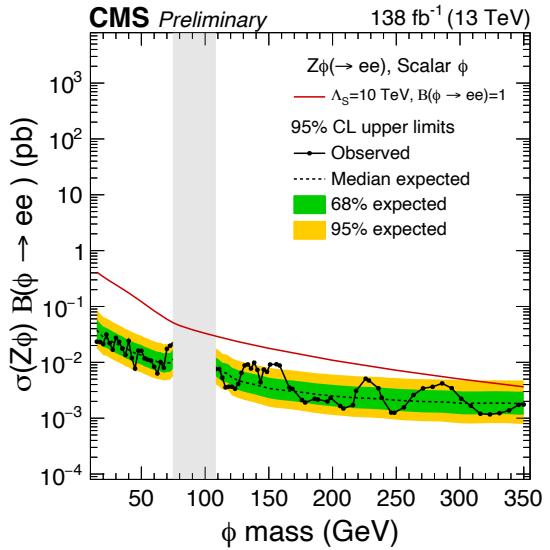
Region name (label)	ParticleNet discriminator	
	H jet	Yjet
Signal region 1 (SR1)	>0.98	>0.98
Signal region 2 (SR2) (excludes SR1)	>0.94	>0.94
Sideband 1 (SB1)	>0.98	<0.94
Sideband 2 (SB2)	>0.94	<0.94
Validation signal-like 1 (VS1)		>0.98
Validation signal-like 2 (VS2)	0.8–0.94	0.94–0.98
Validation sideband 1 (VB1)		<0.94
Validation signal-like 3 (VS3)		>0.98
Validation signal-like 4 (VS4)	0.6–0.8	0.94–0.98
Validation sideband 2 (VB2)		<0.94



Additional Singlet: $V\phi$, $t\bar{t}\phi$

Additional materials

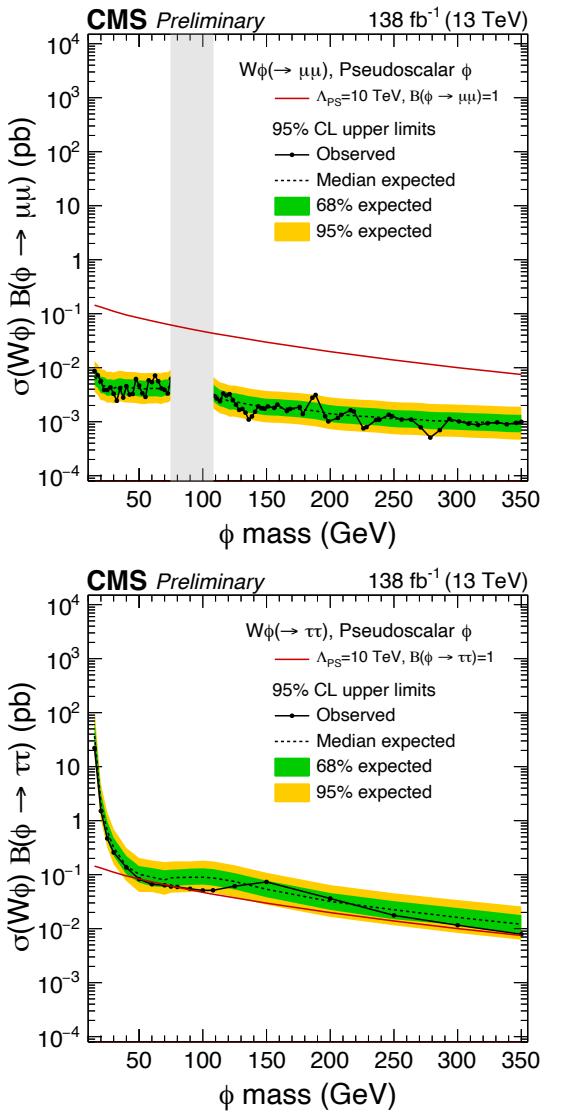
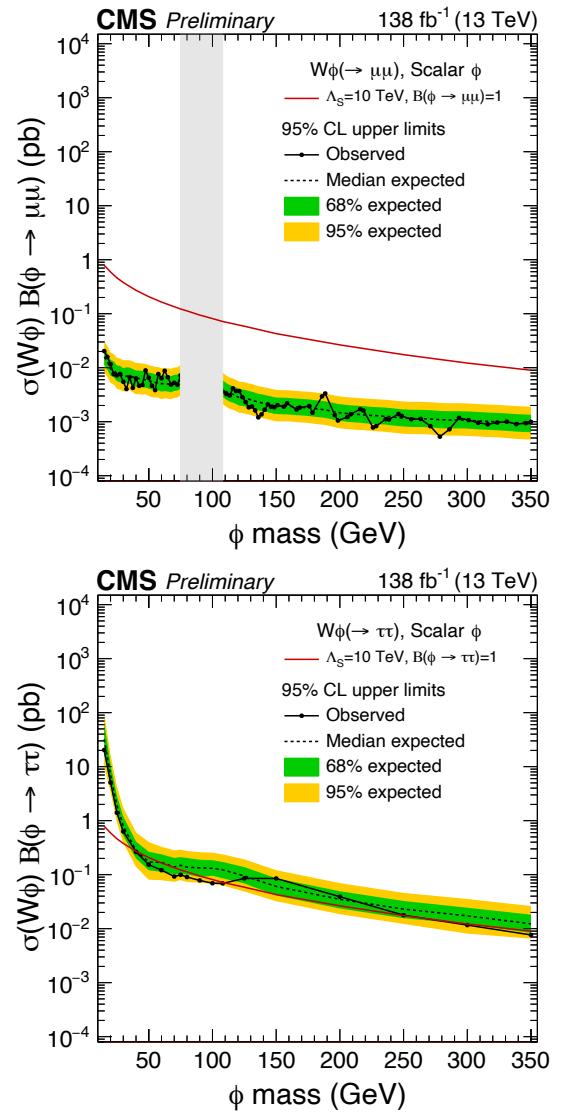
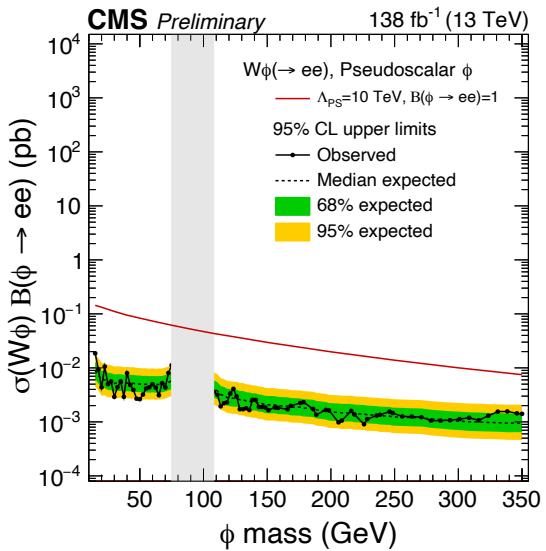
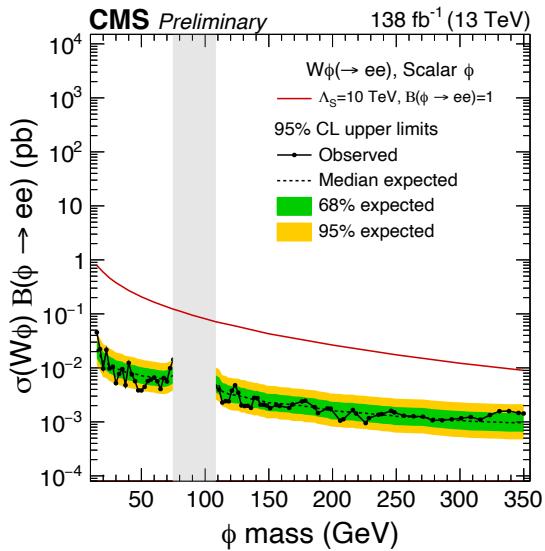
- $Z\phi$ limits



Additional Singlet: $V\phi$, $tt\phi$

Additional materials

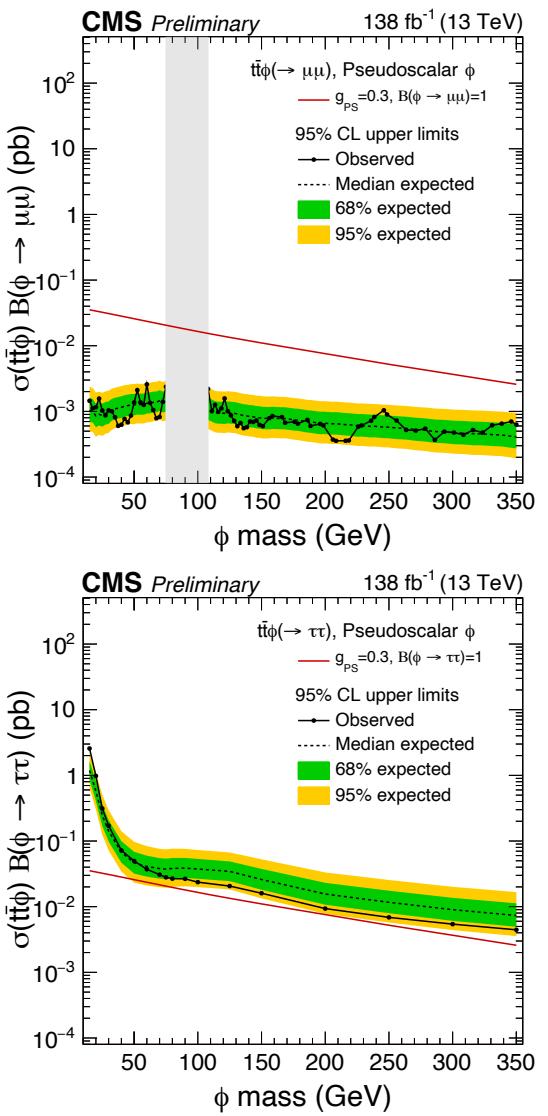
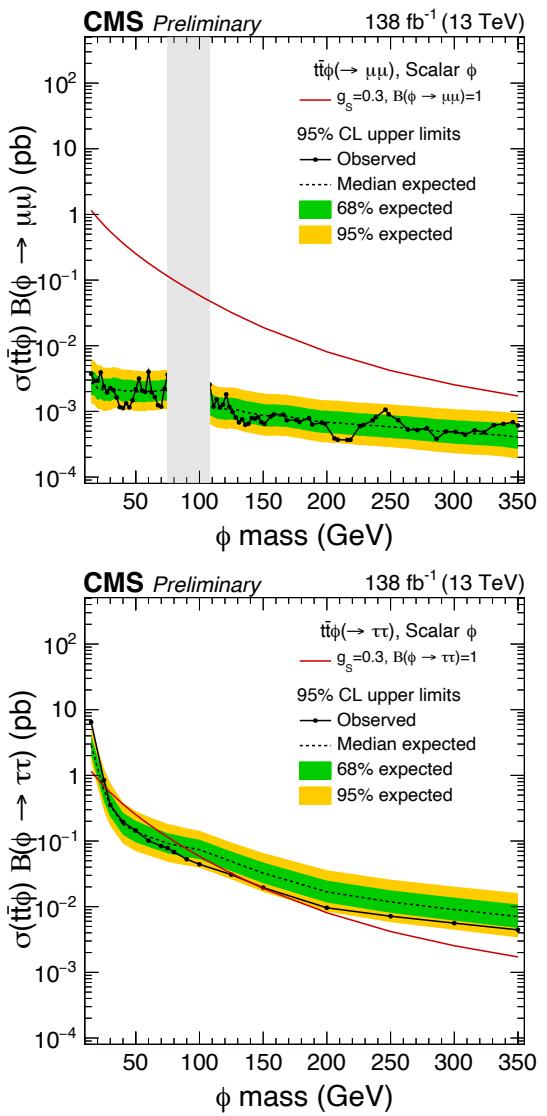
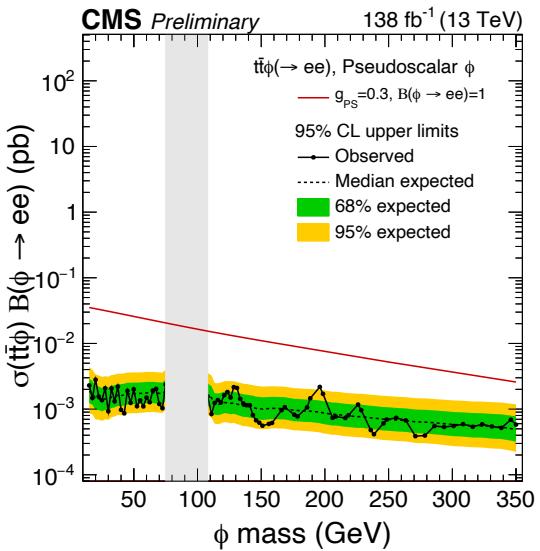
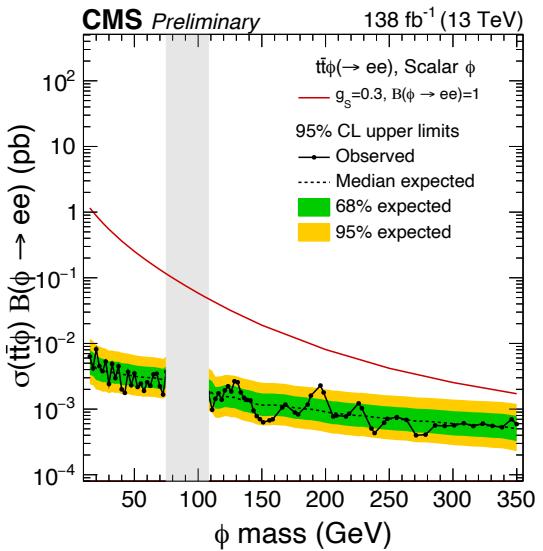
- $W\phi$ limits



Additional Singlet: $V\phi$, $t\bar{t}\phi$

Additional materials

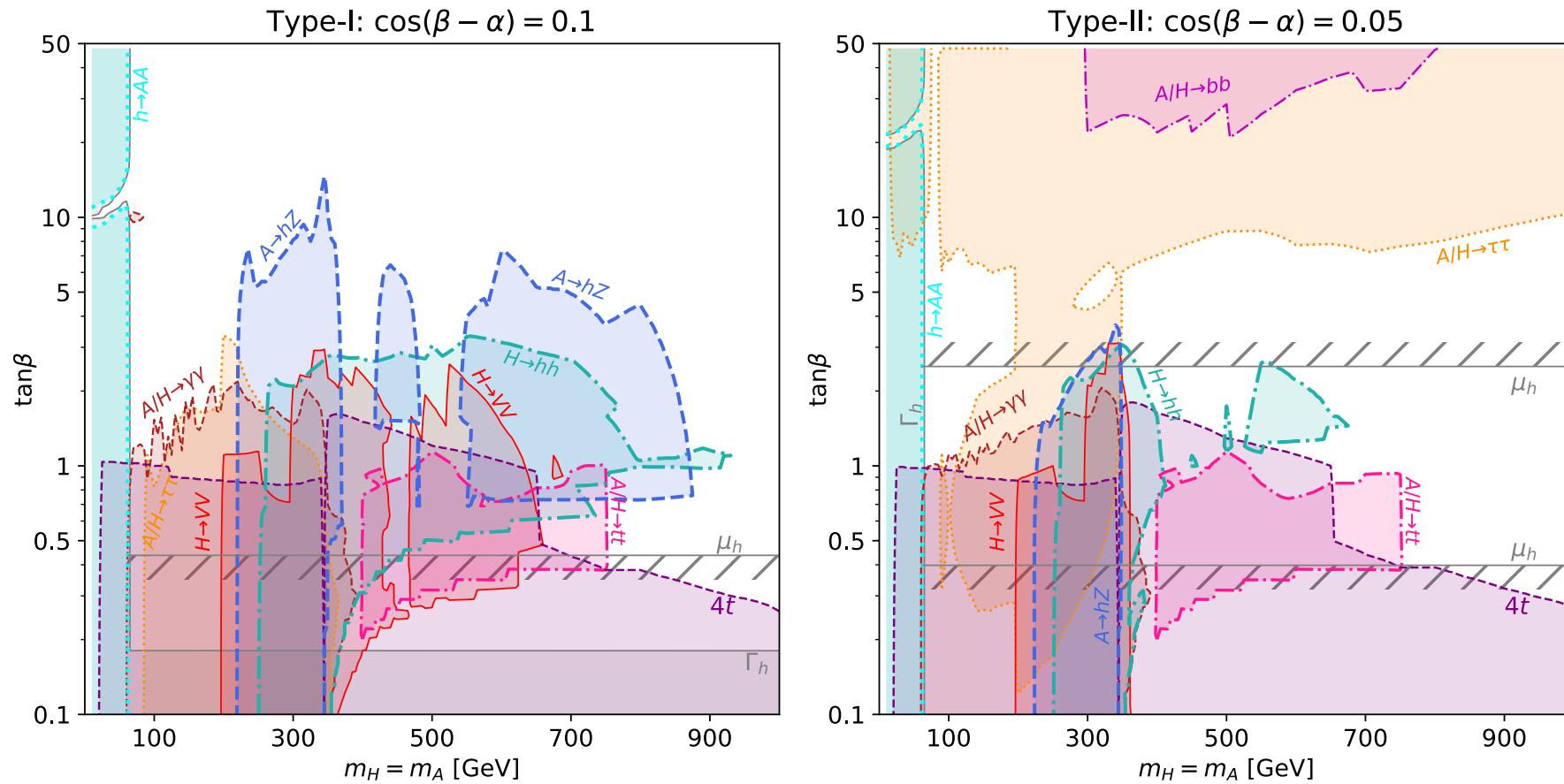
- $t\bar{t}\phi$ limits



Additional materials

- Constraints, LHC Run 2 2016 data

5



Additional materials

- Constraints, LHC CMS Run 2 2016 data

