

# SEARCHES FOR ADDITIONAL HIGGS BOSONS DECAYING TO TAU LEPTONS AT THE LHC

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on behalf of CMS and ATLAS collaborations

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# Introduction

Discovering of  $h(125)$  milestone for particle physics and the LHC program

**Investigate properties of the observed Higgs boson.**

Is  $h(125)$  THE Higgs boson of the SM?

- ▶ Properties different from SM expectation.
- ▶ Exotic decays not expected within the SM.

**Search for complex Higgs sector.**

Is  $h(125)$  the ONLY Higgs boson of the SM?

- ▶ More than one  $SU_L(2)$  doublet?
- ▶ Prediction of many BSM models (among those SUSY).

**Rich program to search for new physics in the Higgs sector.**

# BSM Higgs Sector

## Extending the Higgs sector

SM + singlet

**Electroweak Singlet (EWS):**  
2 CP-even bosons.

SM + doublet

**Two-Higgs Double Models (2HDM):**  
5 Higgs bosons  
( $H, h, A, H^\pm$ )

SM + triplet

**Higgs Triplet:**  
charged, doubly-charged, and neutral bosons.

### 2HDM+S:

Two Higgs Doublets and an additional complex singlet (e.g. NMSSM)

### MSSM:

Higgs Sector is Type-II 2HDM. Current common benchmark is hMSSM.

### MSSM:

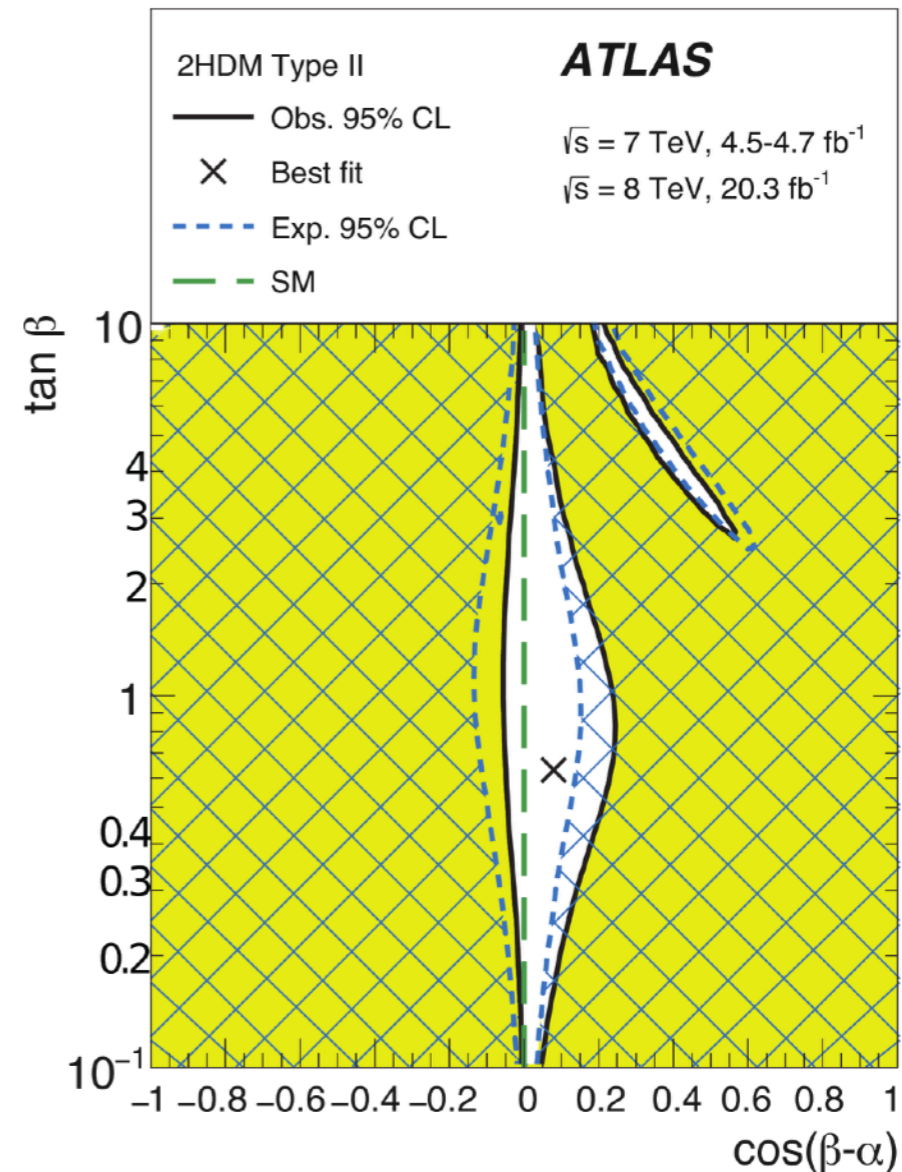
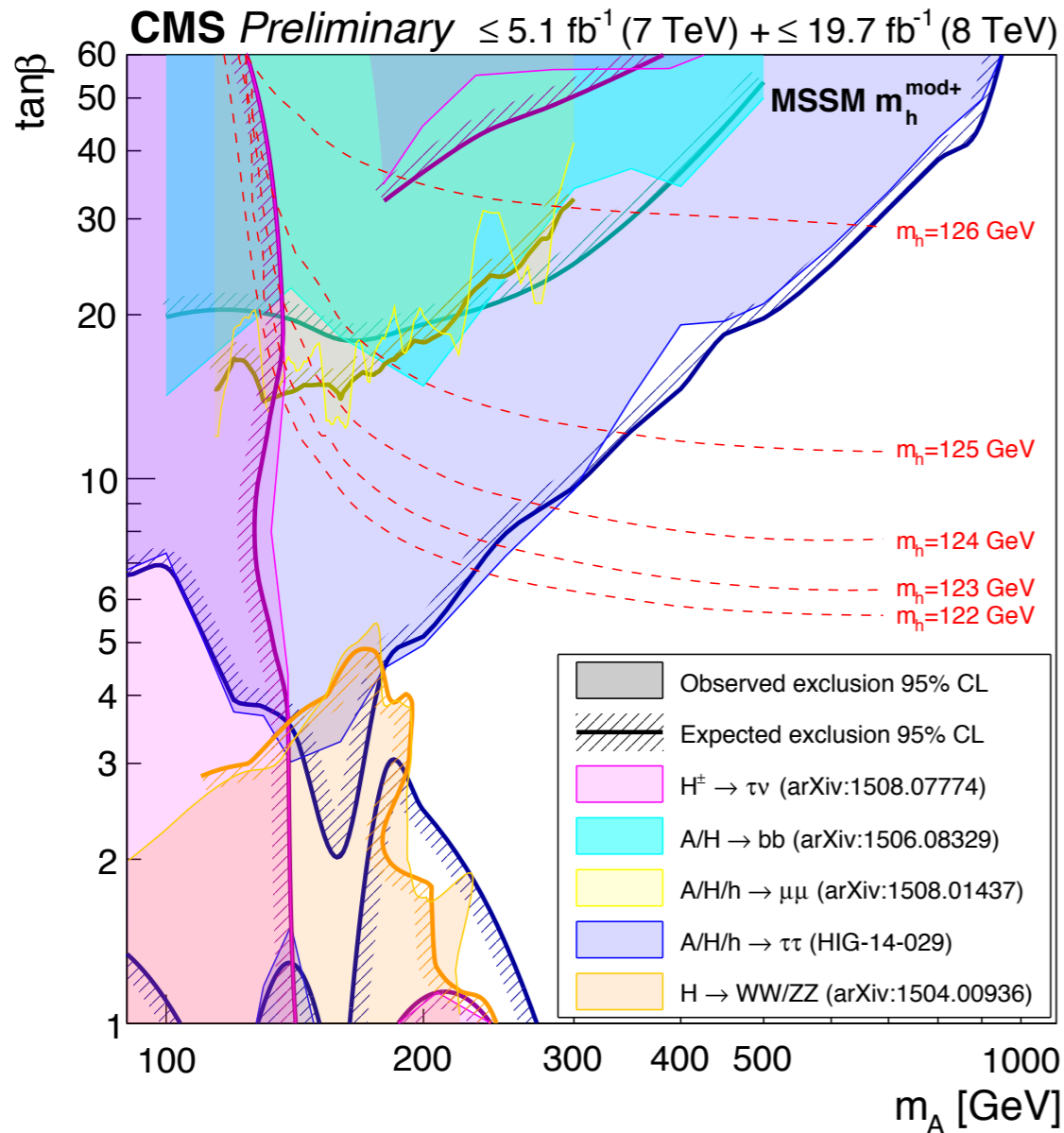
- ▶ At tree level two free parameters:  $m_A$  and  $\tan\beta$  (doublets VEVs ratio)
- ▶ couplings parametrised by  $\beta$  and  $\alpha$  (mixing angle between  $h$  and  $H$ )

### NMSSM

- ▶ 6 free parameter
- ▶ More complex phenomenology wrt MSSM

# RUN1 BSM Higgs Sector

Many searches were performed in Run1, with 7 and 8 TeV datasets at the LHC.



$\cos(\beta - \alpha) < 0.1$  from  $h_{125}$  couplings

**Down-type Fermionic channels become interesting**

# Analyses covered

## MSSM Searches

**MSSM  $H/A/h \rightarrow \tau\tau$**

ATLAS: [JHEP 01 \(2018\) 055](#)

CMS: [arXiv:1803.06553](#)

**$H^\pm \rightarrow \tau\nu$**

ATLAS: [arXiv:1807.07915](#)

CMS: [CMS-PAS-HIG-16-031](#)

## NMSSM Searches

**$h(125) \rightarrow aa \rightarrow \mu\mu\tau\tau$**

CMS: [arXiv:1805.04865](#)

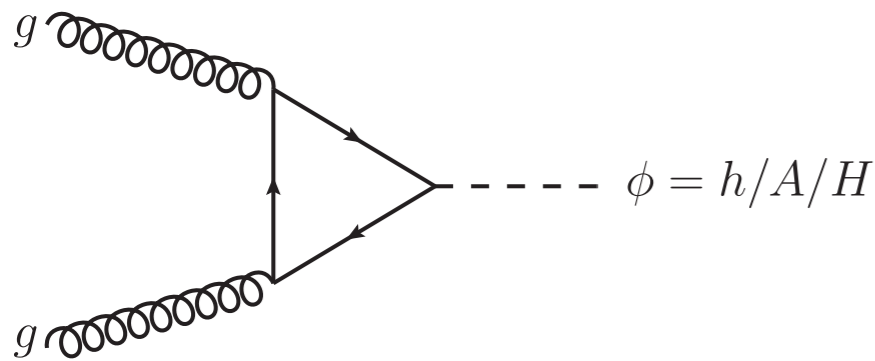
**$h(125) \rightarrow aa \rightarrow bb\tau\tau$**

CMS: [arXiv:1805.10191](#)

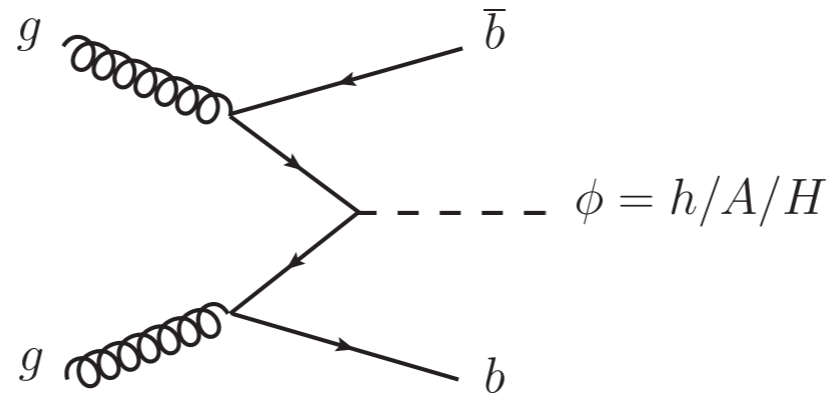
**MSSM H/A/h  $\rightarrow$   $\tau\tau$**

# MSSM $H/A/h \rightarrow \tau\tau$

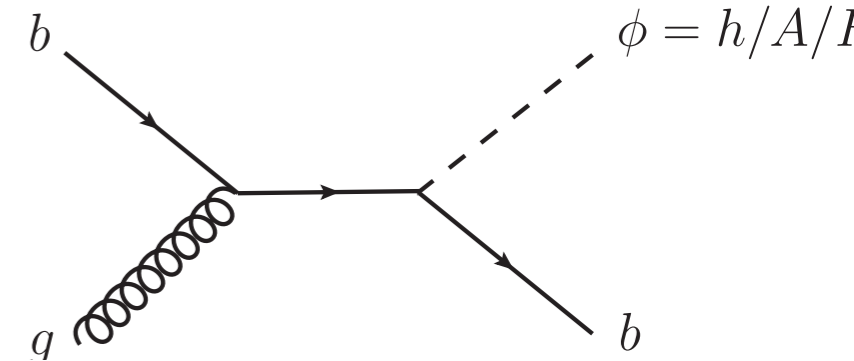
ATLAS: [JHEP 01 \(2018\) 055](#)  
 CMS: [arXiv:1803.06553](#)



**gg fusion**



**bb associated production**



$\tau\tau$  decay mode provides sensitivity in MSSM at high  $\tan\beta$ , and in 2HDM at the alignment limit.

## CMS

- ▶ Range: 90 GeV ÷ 3.2 TeV
- ▶ Final states:  $e\mu, \mu\tau_h, e\tau_h, \tau_h\tau_h$

## ATLAS

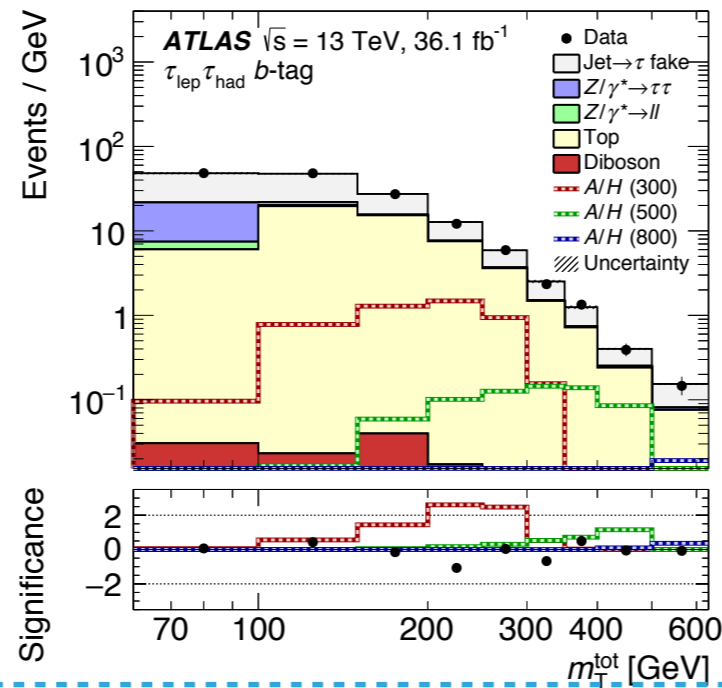
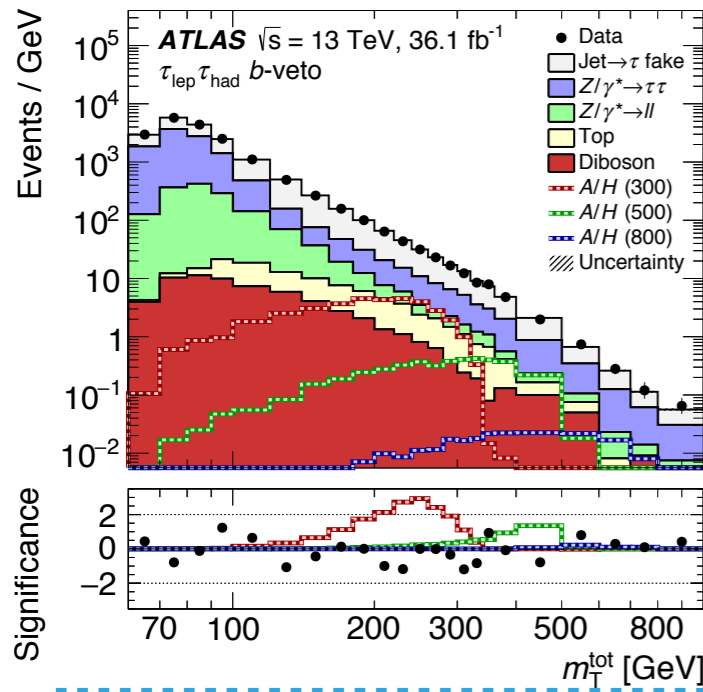
- ▶ Range: 200 GeV ÷ 2.25 TeV
- ▶ Final states:  $\mu\tau_h, e\tau_h, \tau_h\tau_h$

## Final Discriminant

$$m_T^{\text{total}} = \sqrt{m_T^2(\tau_1, \tau_2) + m_T^2(\tau_1, E_T^{\text{miss}}) + m_T^2(\tau_2, E_T^{\text{miss}})}$$

# CATEGORIZATION

Categories exploit topological kinematic peculiarities of MSSM motivated production



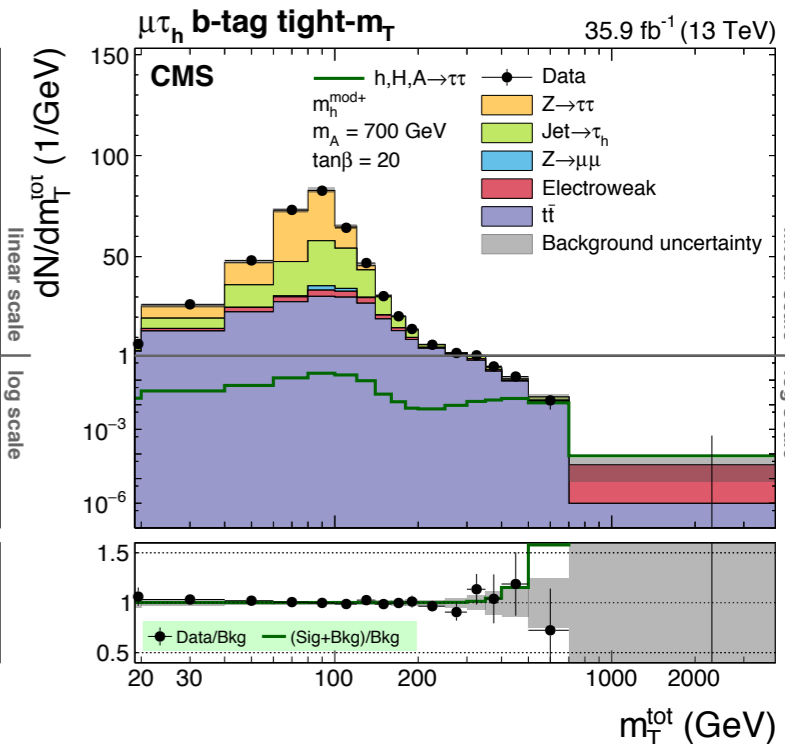
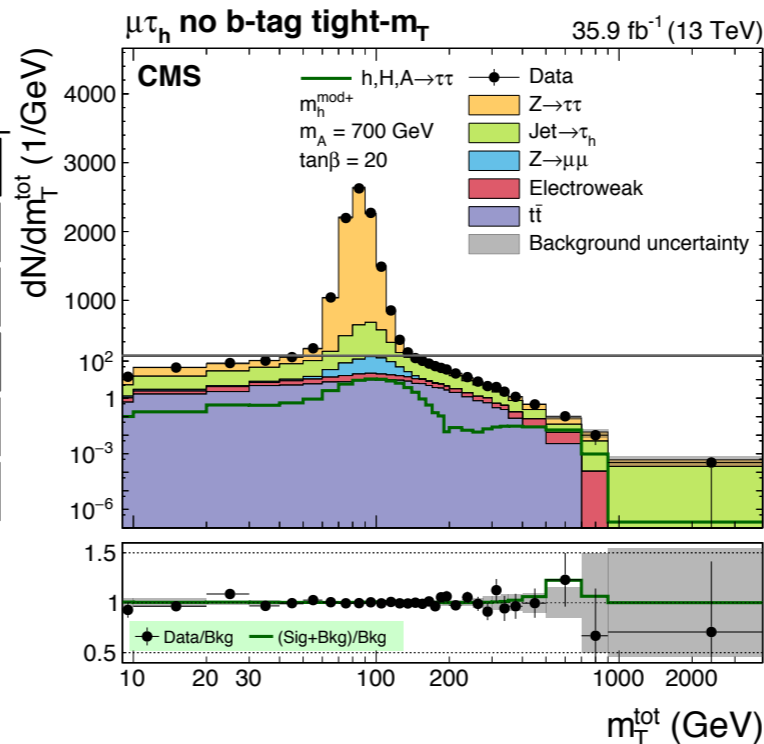
**ATLAS**

- ▶ *b*tag category
- ▶ *b*tag-veto category

**CMS**

	No <i>b</i> -tag			<i>b</i> -tag		
	Low- $D_\zeta$	Medium- $D_\zeta$	High- $D_\zeta$	Low- $D_\zeta$	Medium- $D_\zeta$	High- $D_\zeta$
$H \rightarrow \tau\tau \rightarrow e\mu$						
$H \rightarrow \tau\tau \rightarrow e\tau_h$	Loose- $m_T$	Tight- $m_T$		Loose- $m_T$	Tight- $m_T$	
$H \rightarrow \tau\tau \rightarrow \mu\tau_h$	Loose- $m_T$	Tight- $m_T$		Loose- $m_T$	Tight- $m_T$	
$H \rightarrow \tau\tau \rightarrow \tau_h\tau_h$						
$Z \rightarrow \mu\mu$	Control region			Control region		
$t\bar{t}(e\mu)$	Control region					

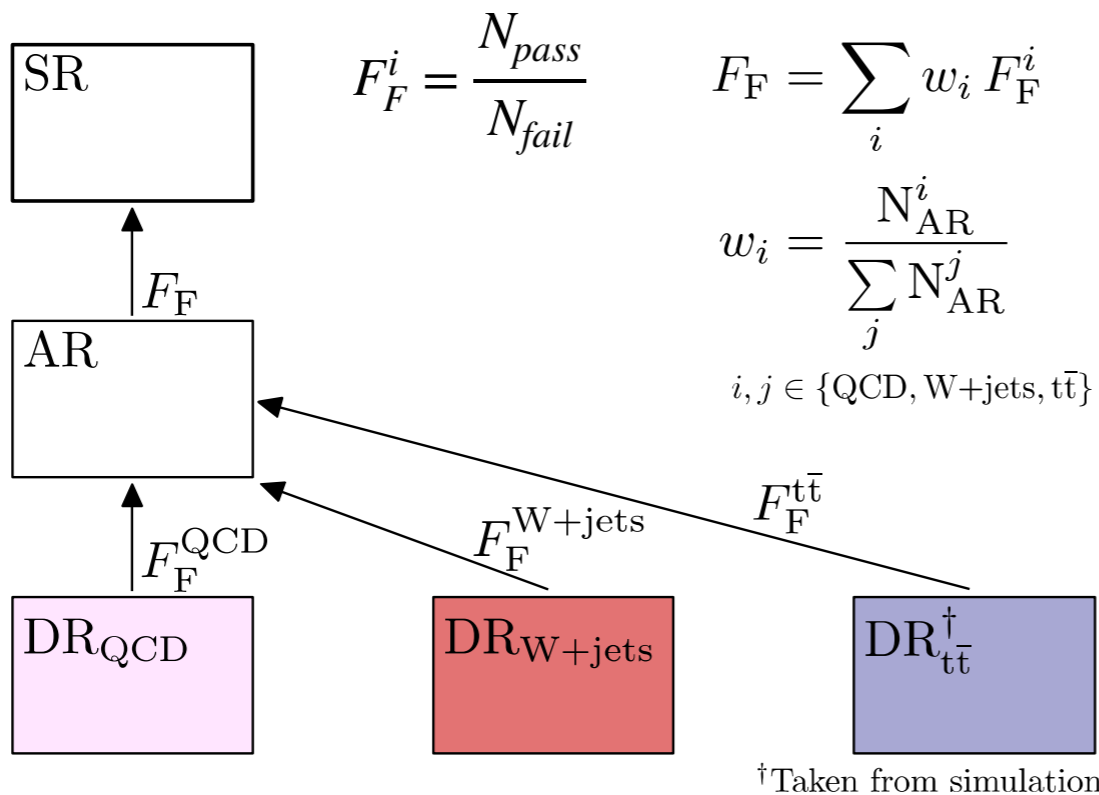
Signal region (SR)  
 Control region



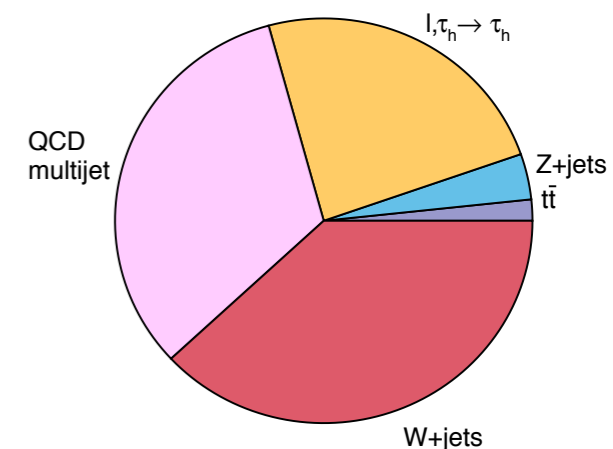


# FAKE FACTOR METHOD

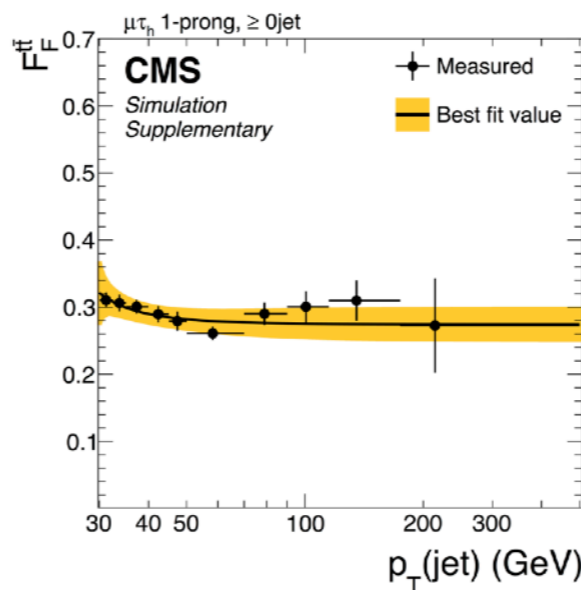
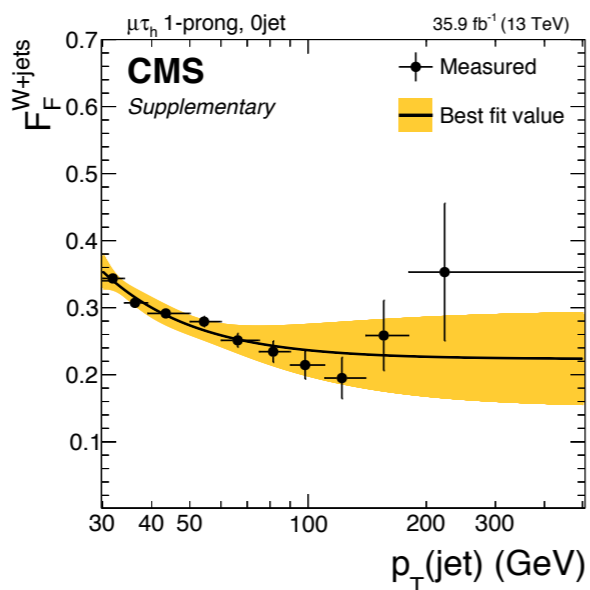
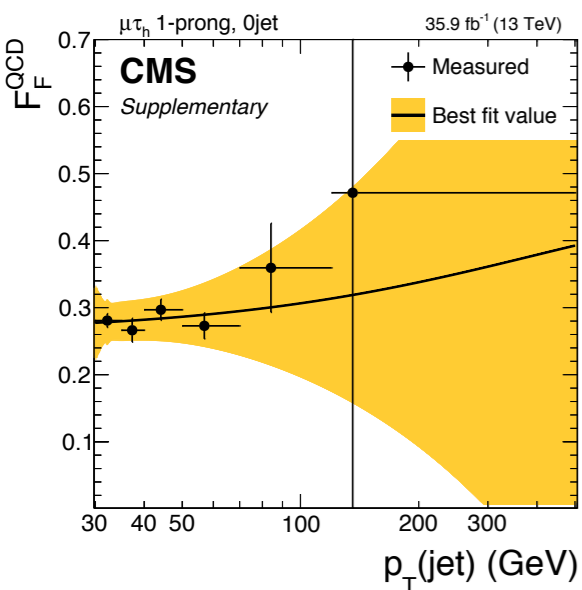
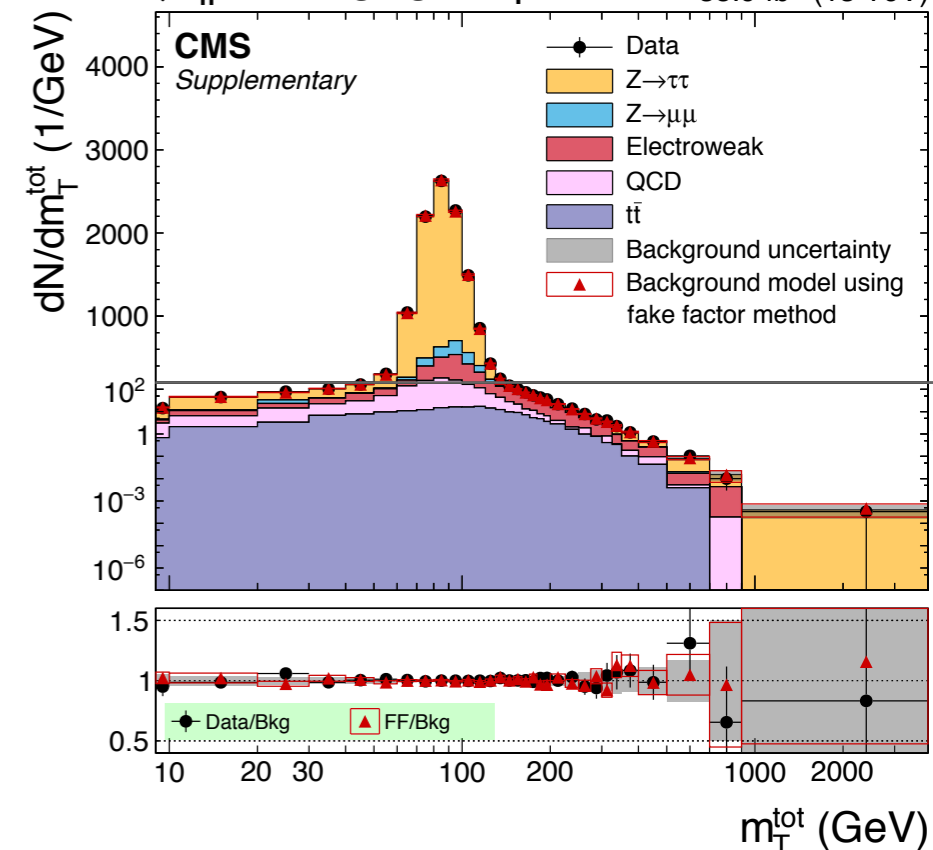
A large fraction of the backgrounds can be attributed to jets misidentified as  $\tau_h$  decays



$\mu\tau_h$  no b-tag tight- $m_T$

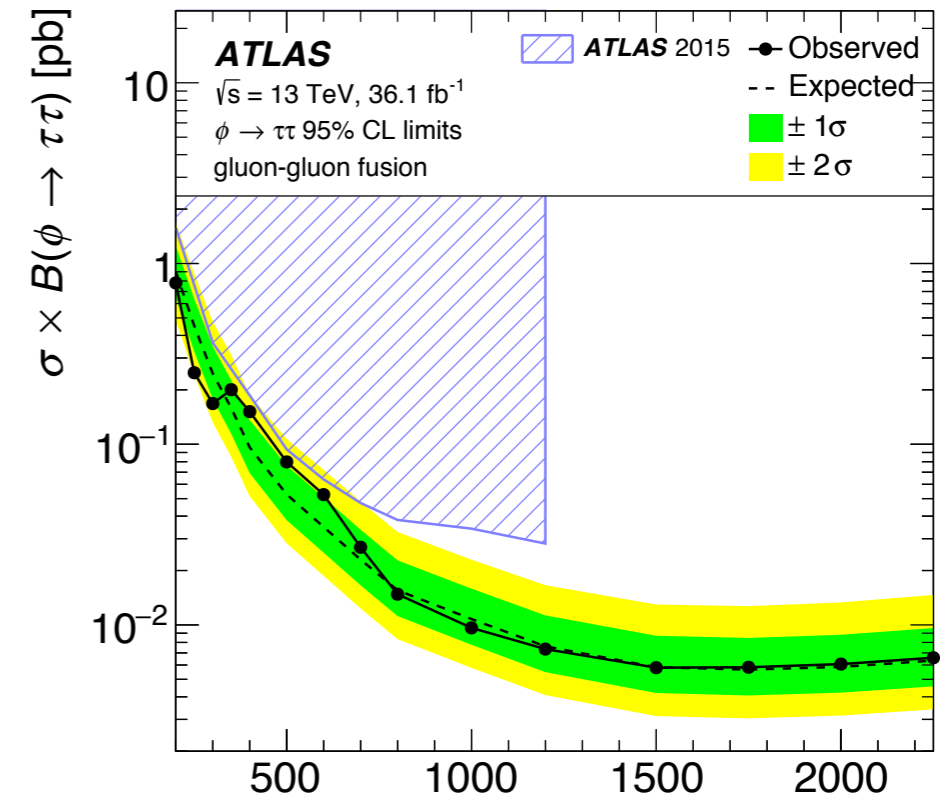
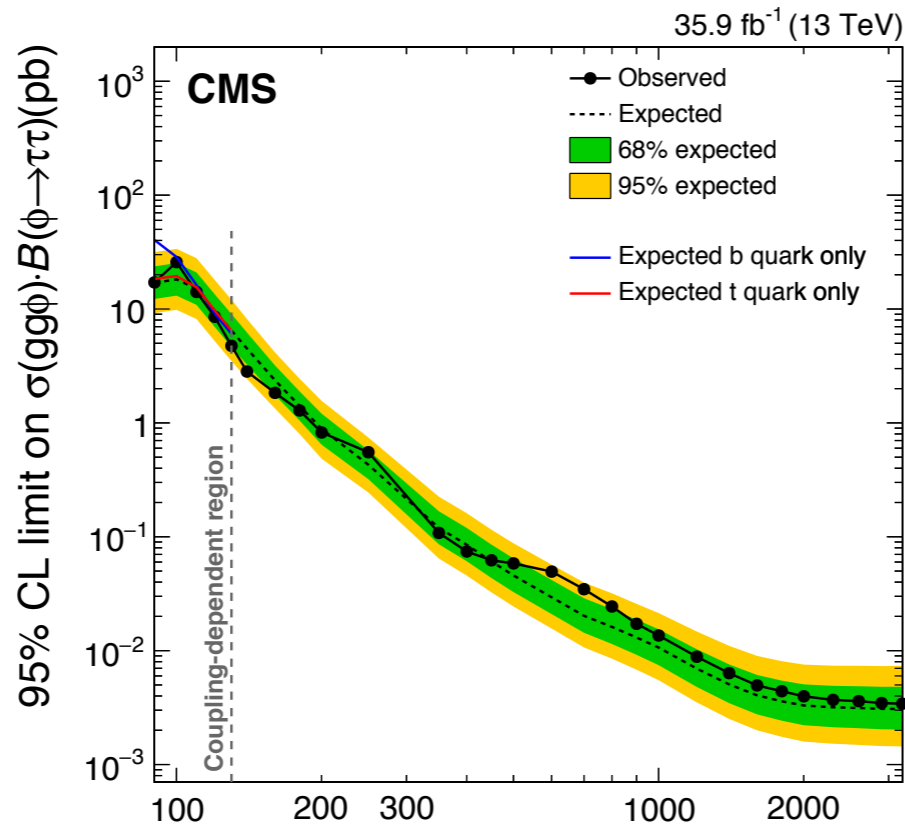


$\mu\tau_h$  no b-tag tight- $m_T$  35.9 fb<sup>-1</sup> (13 TeV)

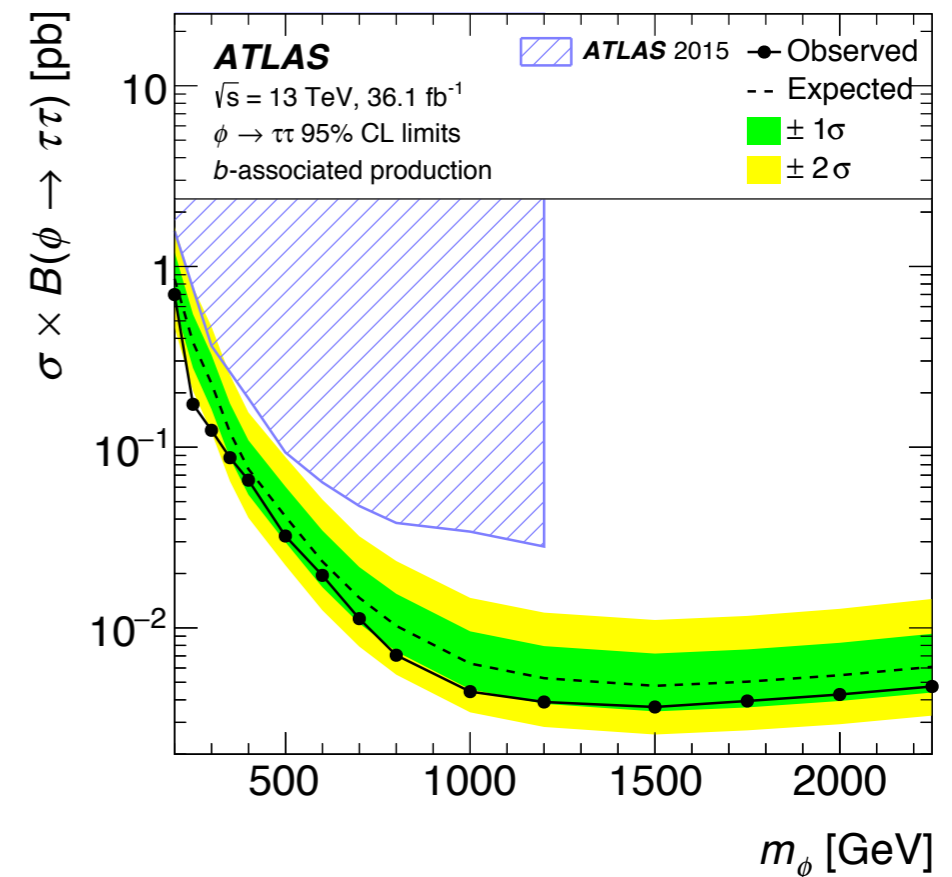
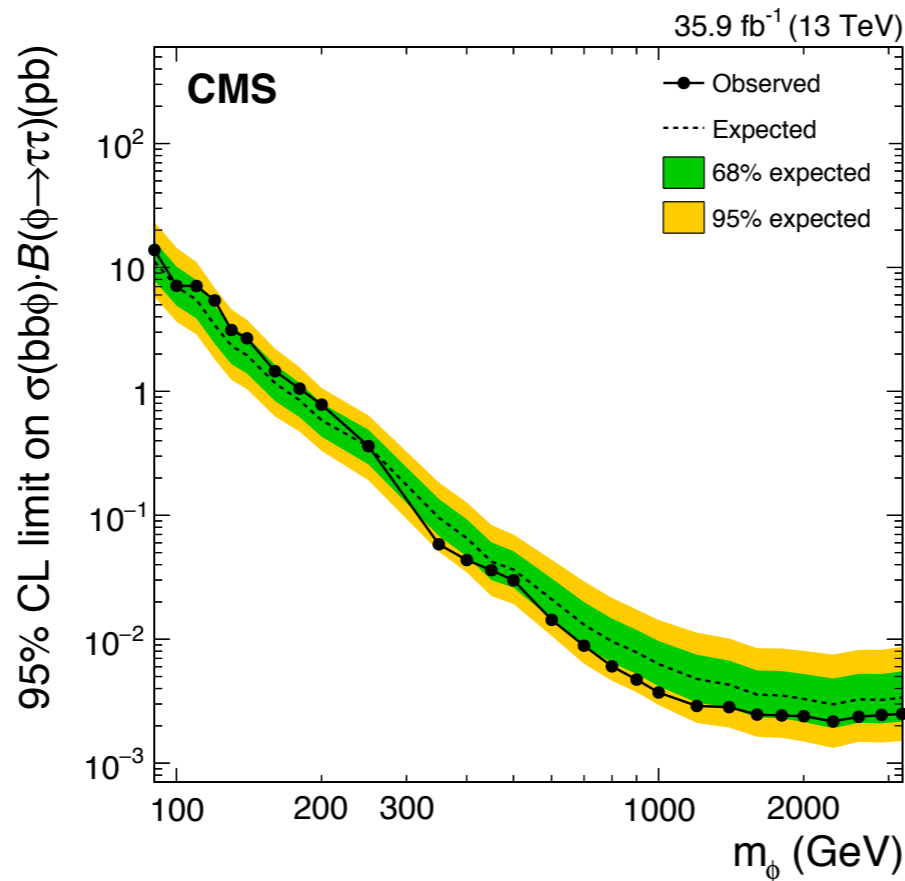


# MODEL INDEPENDENT LIMITS

gluon  
fusion

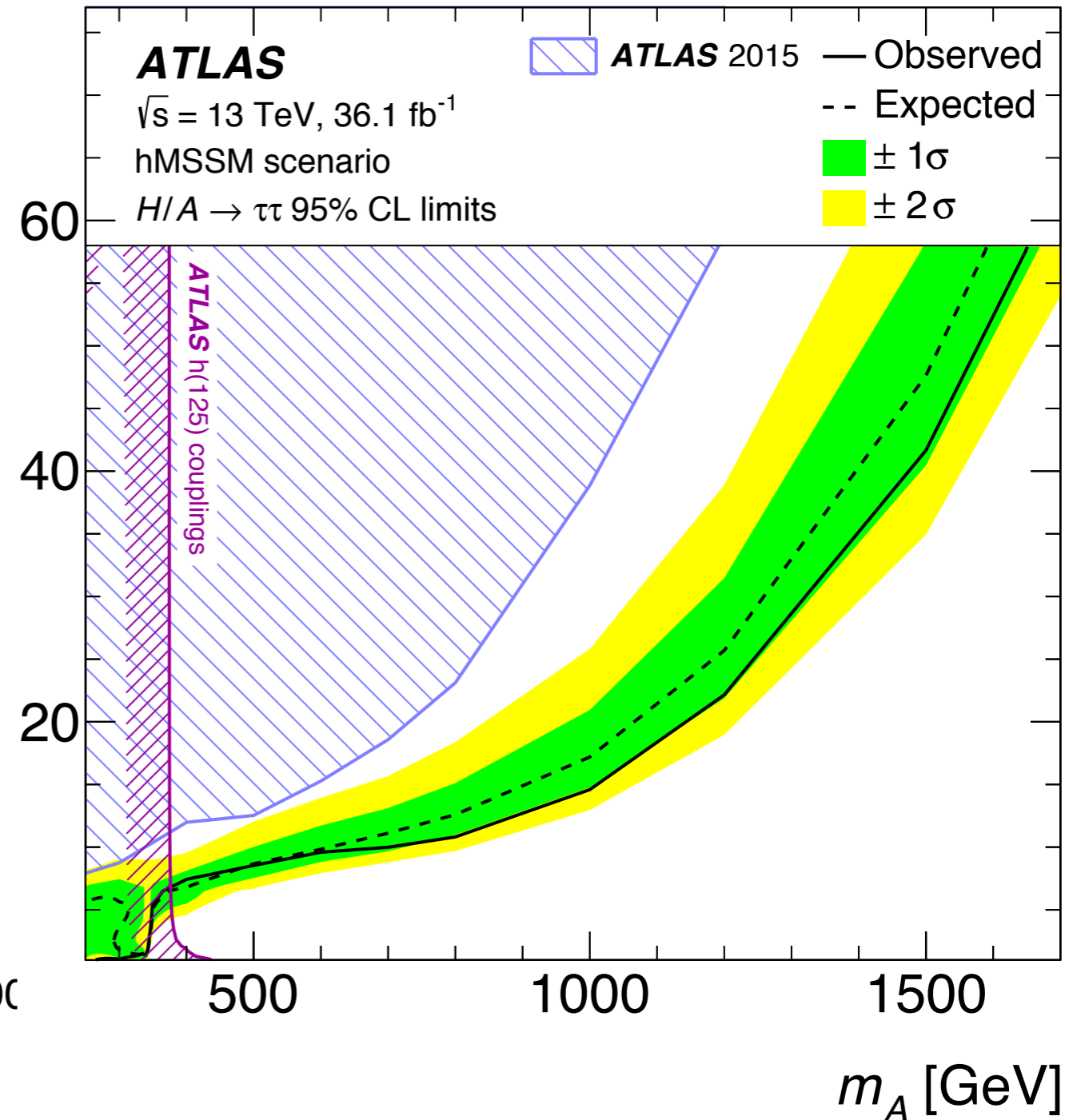
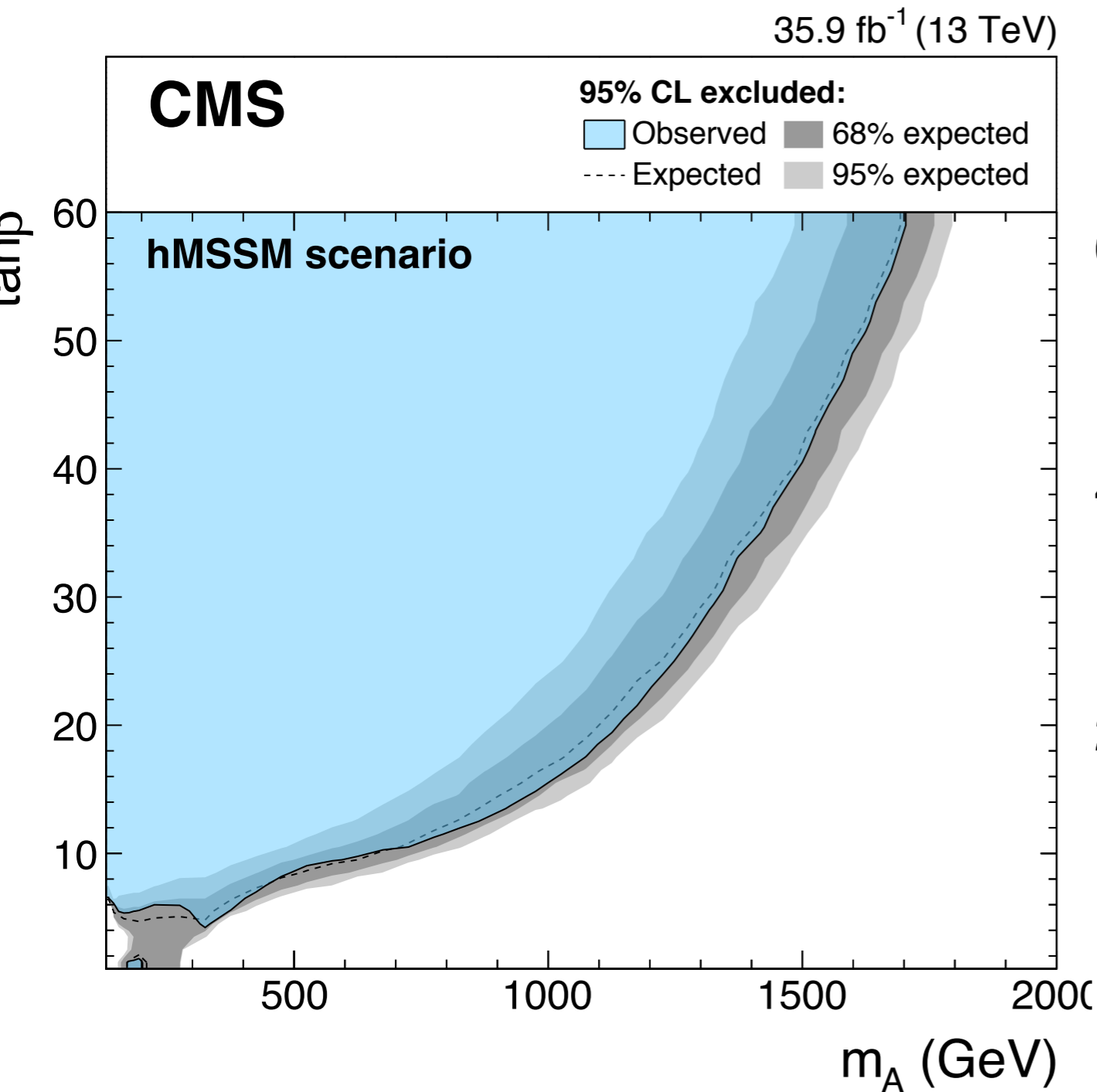


b associated  
production

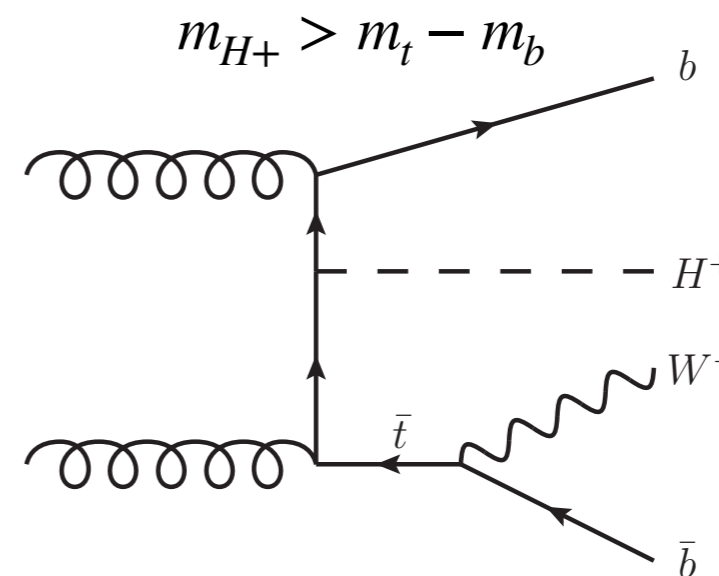
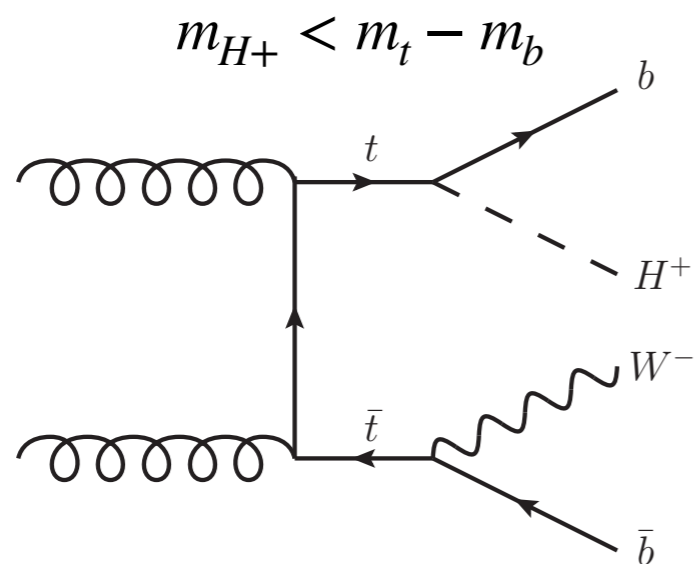


# MODEL DEPENDENT LIMITS

Model independent limits interpreted in the hMSSM  
Exclusion contours in the  $m_A$ - $\tan\beta$  plane



# Charged Higgs



$H^\pm \rightarrow \tau\nu$  decay channel represents a clean signature and substantial BR ( $\sim 10\%$ ) in several MSSM benchmarks.

### **CMS** (12.6 fb<sup>-1</sup>)

- ▶ Range: 80 GeV ÷ 160 GeV  
180 GeV ÷ 3 TeV
- ▶ Final states:  $\tau_h + \text{jets}$
- ▶ Transverse mass used as discriminant

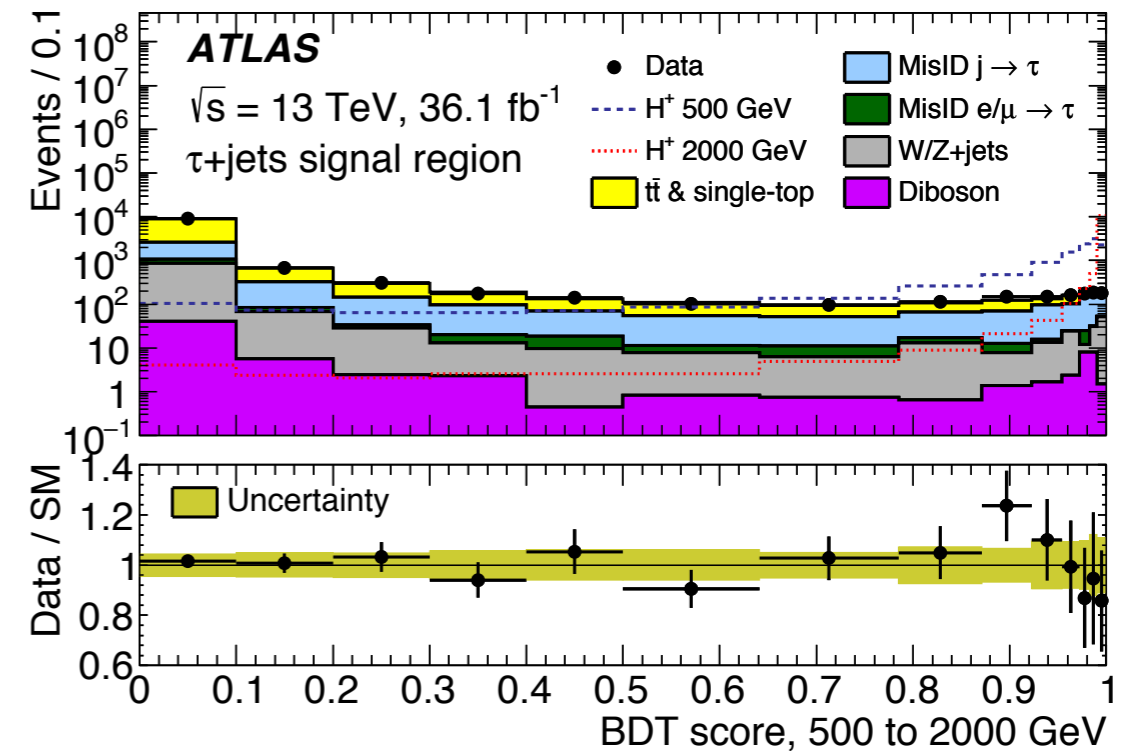
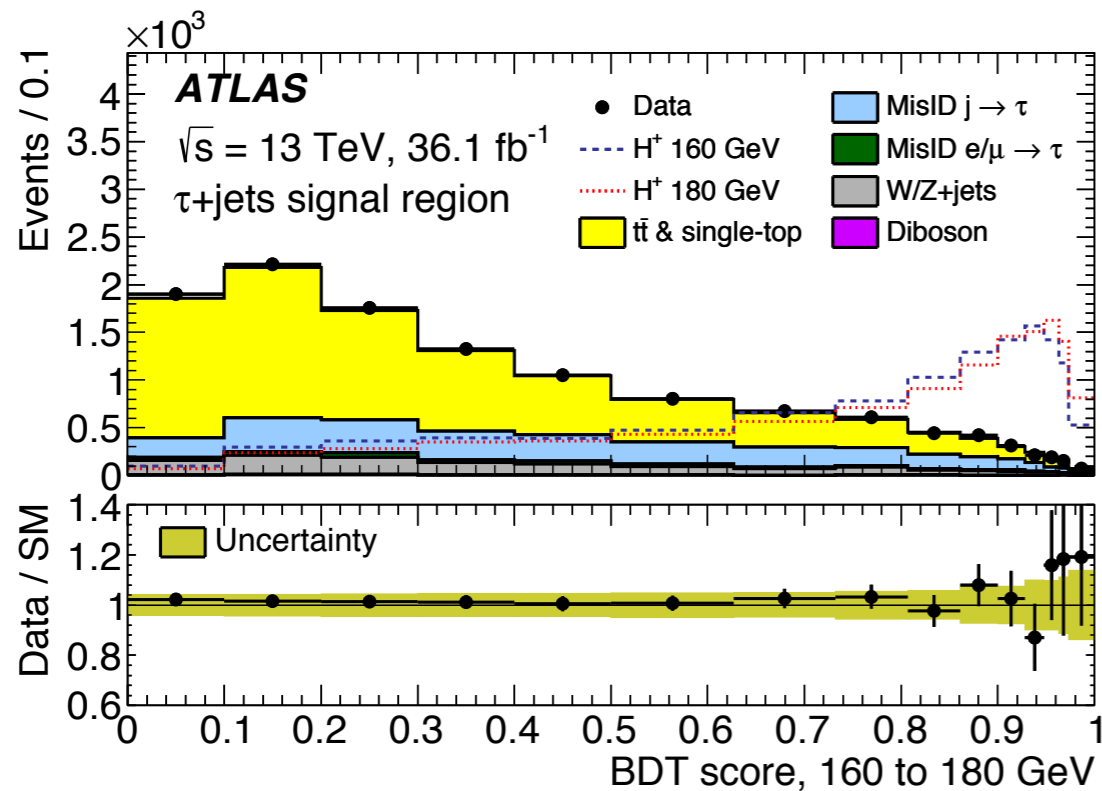
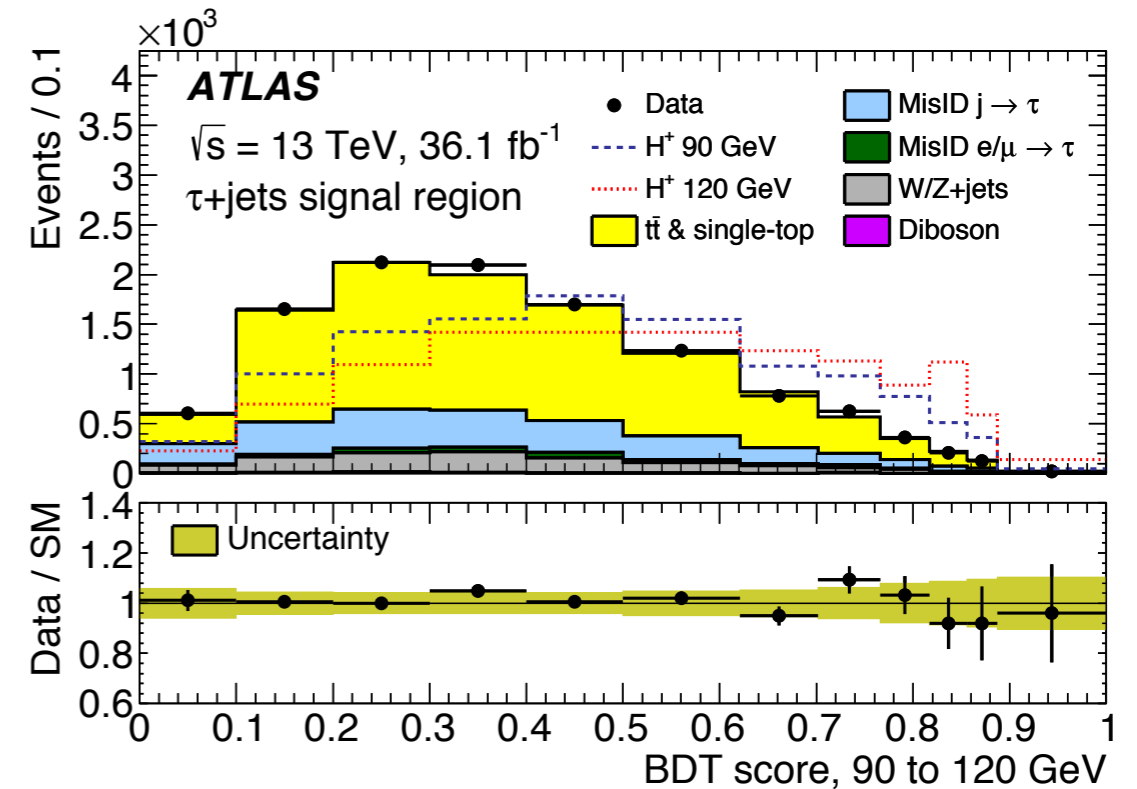
### **ATLAS** (3.2 + 32.9 fb<sup>-1</sup>)

- ▶ Range: 90 GeV ÷ 2 TeV
- ▶ Final states:  $\tau_h + \text{jets} - \tau_h + \text{lepton}$
- ▶ intermediate-mass region included
- ▶ BDT multivariate discriminant

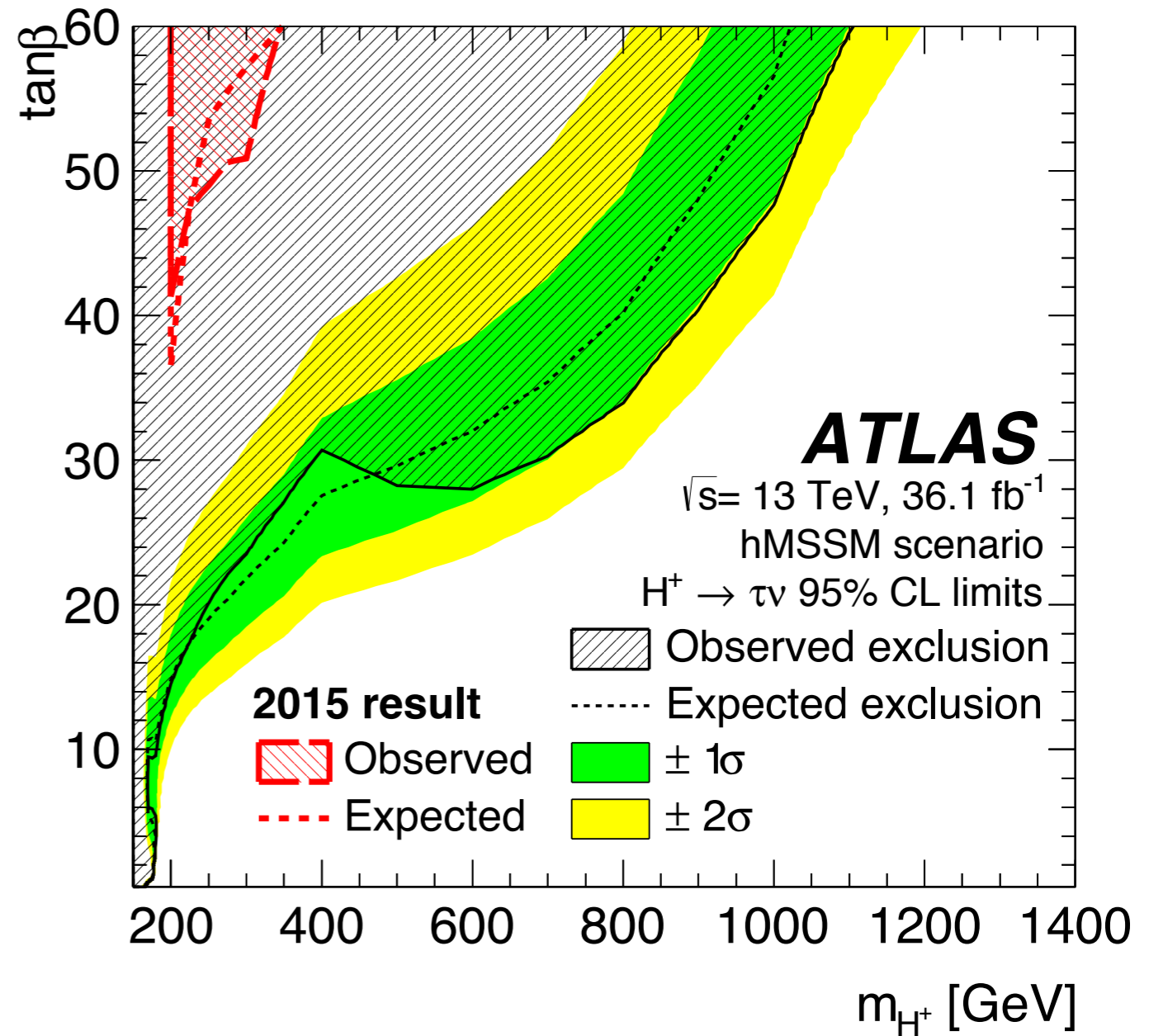
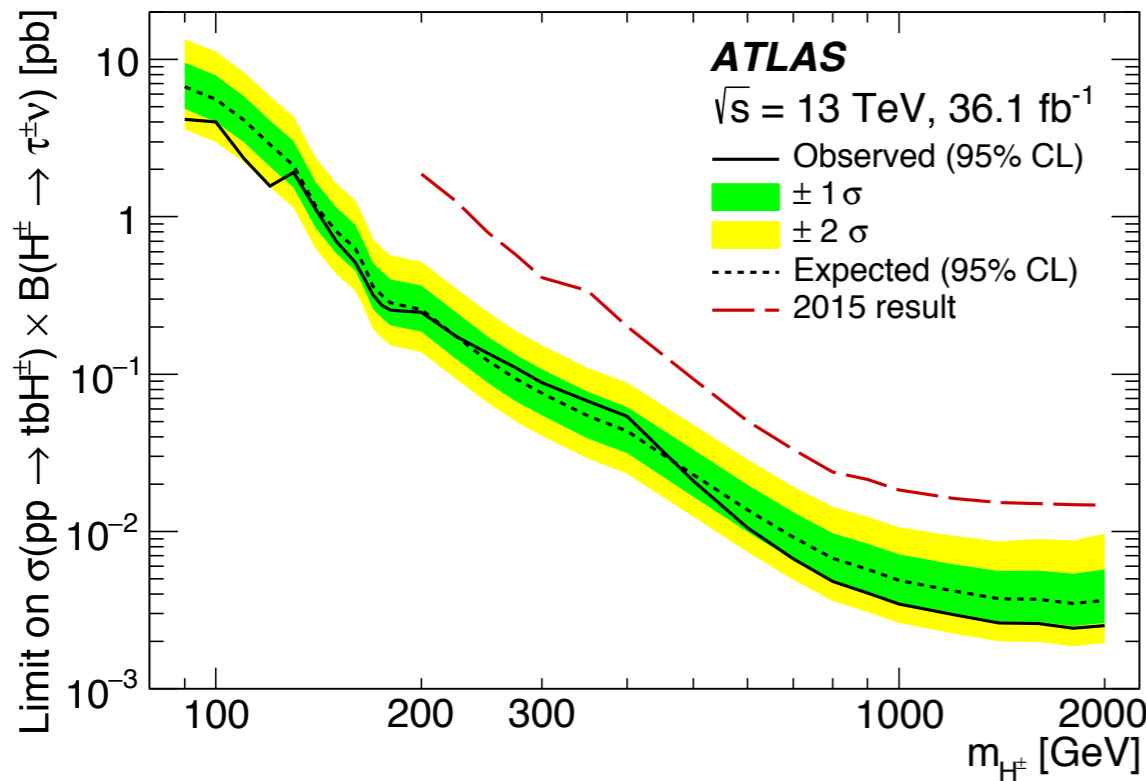
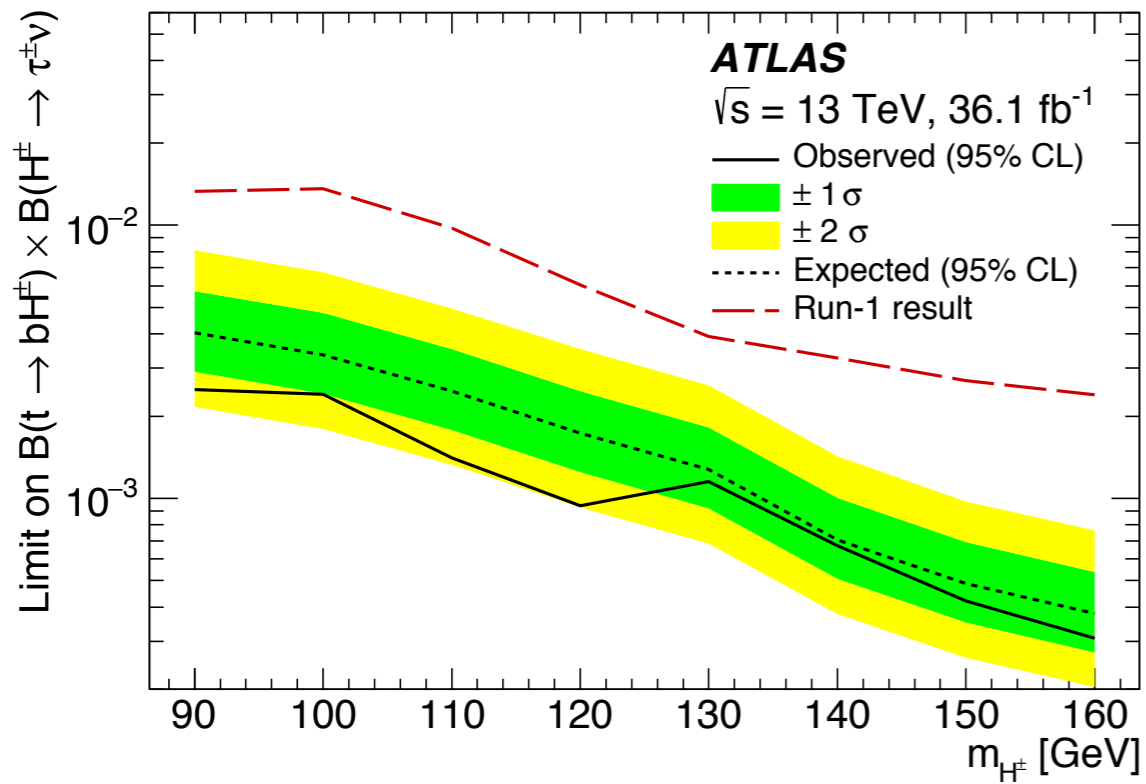
# CATEGORIZATION

**ATLAS** (3.2 + 32.9 fb<sup>-1</sup>)

- ▶ BDT multivariate discriminant
- ▶ 5 macro H<sup>+</sup> mass bins
- ▶ Tau polarisation used  
for 1-prong  $\gamma = \frac{E_T^{\pi^\pm} - E_T^{\pi^0}}{E_T^\tau} \approx 2 \frac{p_T^{\tau\text{-track}}}{p_T^\tau} - 1$
- ▶ Multijet background evaluated using Fake Factor method



# 95% CL LIMITS



► All  $\tan\beta$  excluded  
 for  $m_{H^+} < 160 \text{ GeV}$

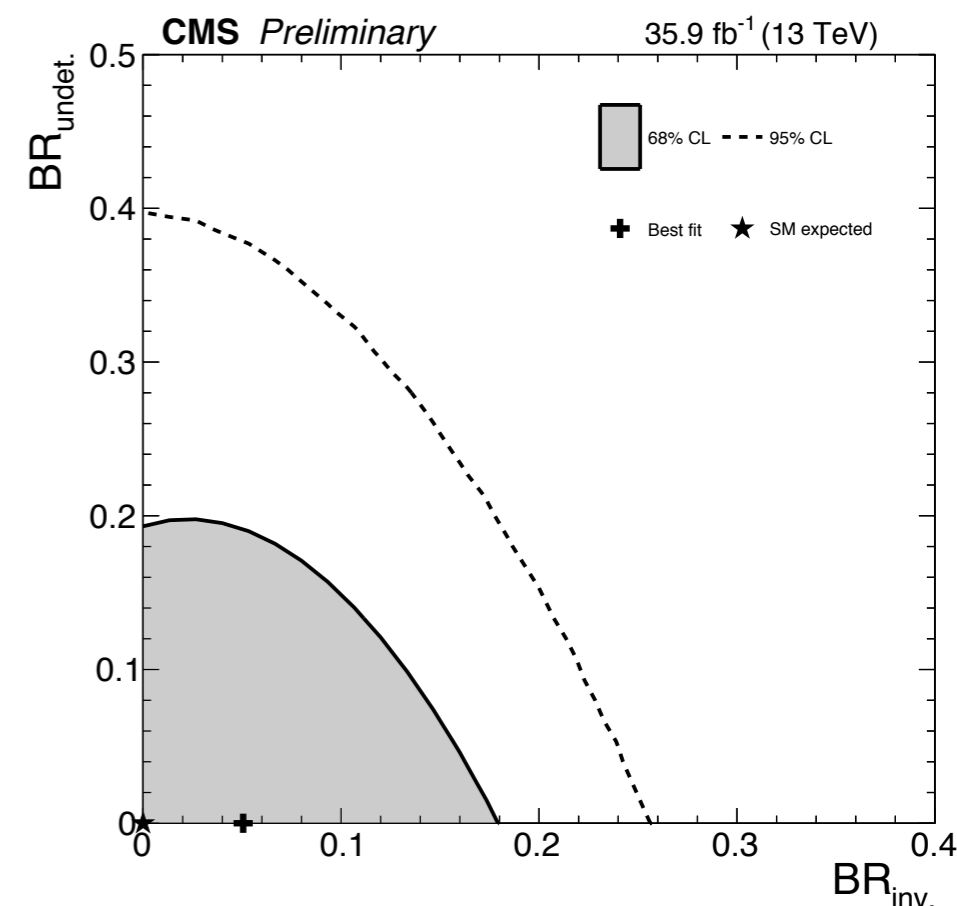
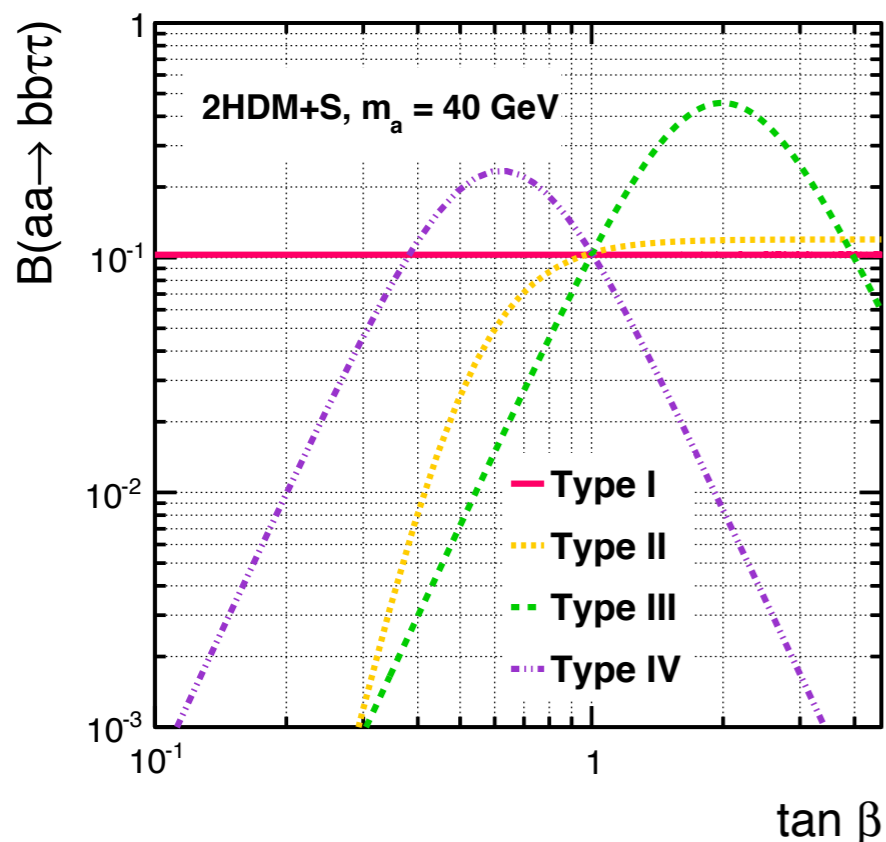
**NMSSM**



# $h(125) \rightarrow aa$

Constraint on from  $BR_{BSM}$  couplings fits still allows for up to 20-30% decays into unobserved particles.

- ▶ Decay chain  $h(125) \rightarrow aa$  offers several constraints during kinematic reconstruction.
- ▶ Plethora of final states analyzed from lowest  $m_a$  possible up to  $m_h/2$



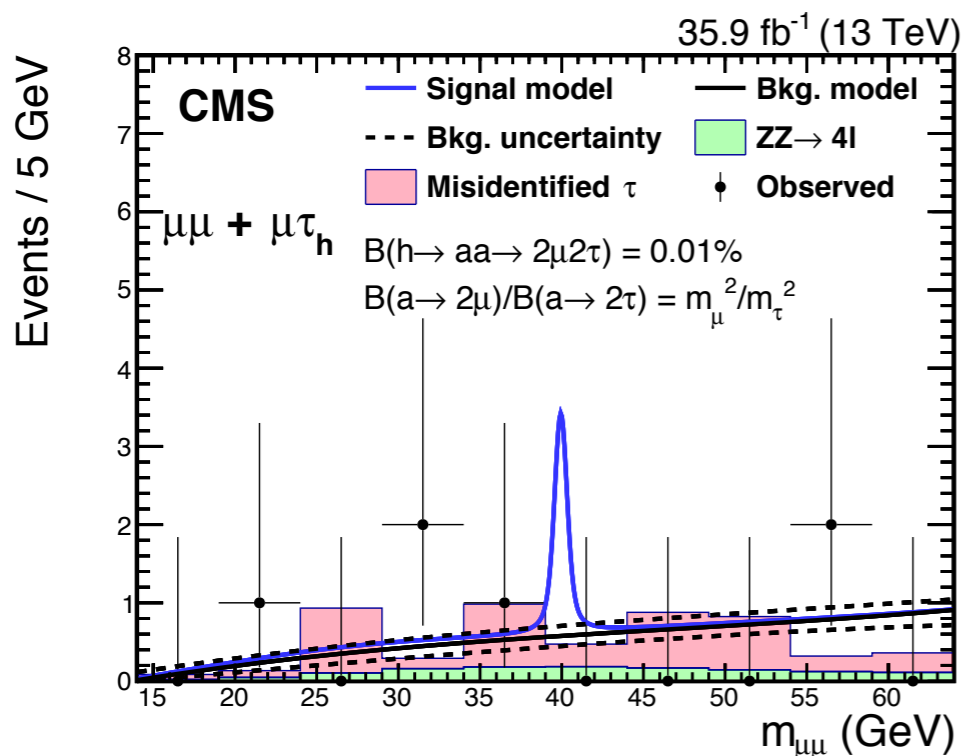
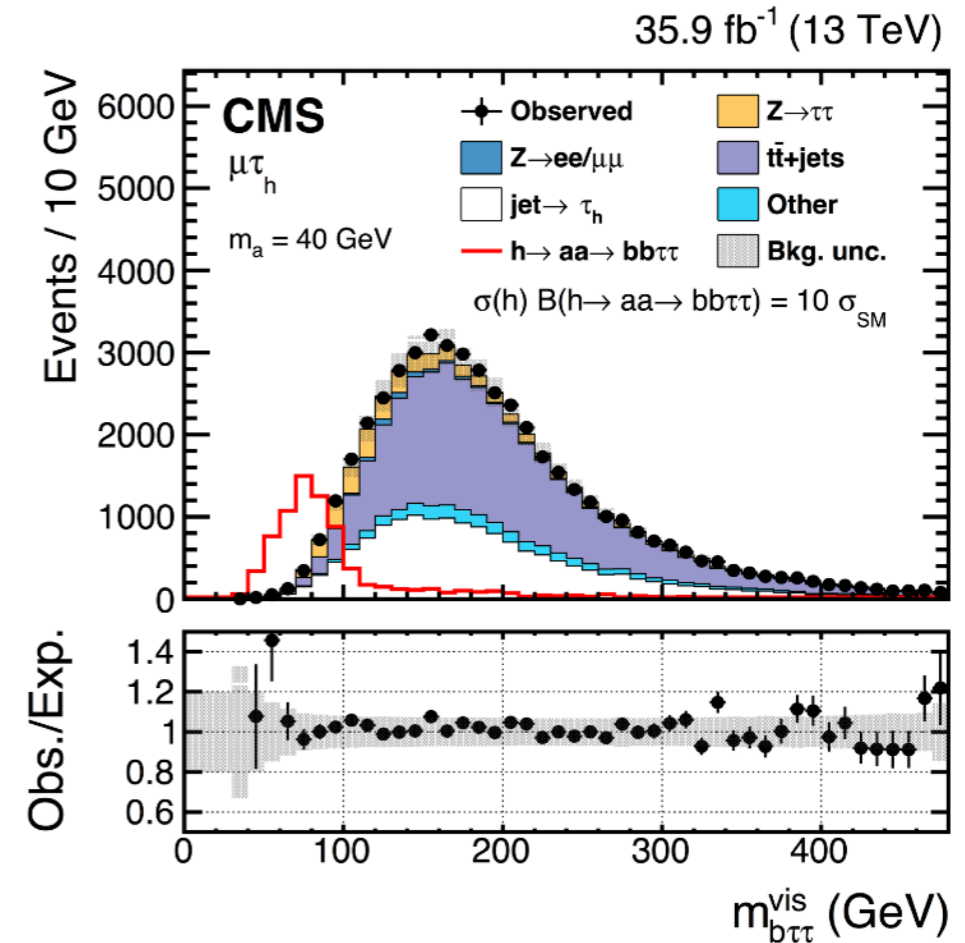
Latest results with 13 TeV and taus in the final state:

- ▶ [arXiv:1805.04865](https://arxiv.org/abs/1805.04865)  $(\mu\mu)(\tau\tau)$
- ▶ [arXiv:1805.10191](https://arxiv.org/abs/1805.10191)  $(bb)(\tau\tau)$

# Analyses strategies

## $(bb)(\tau\tau)$

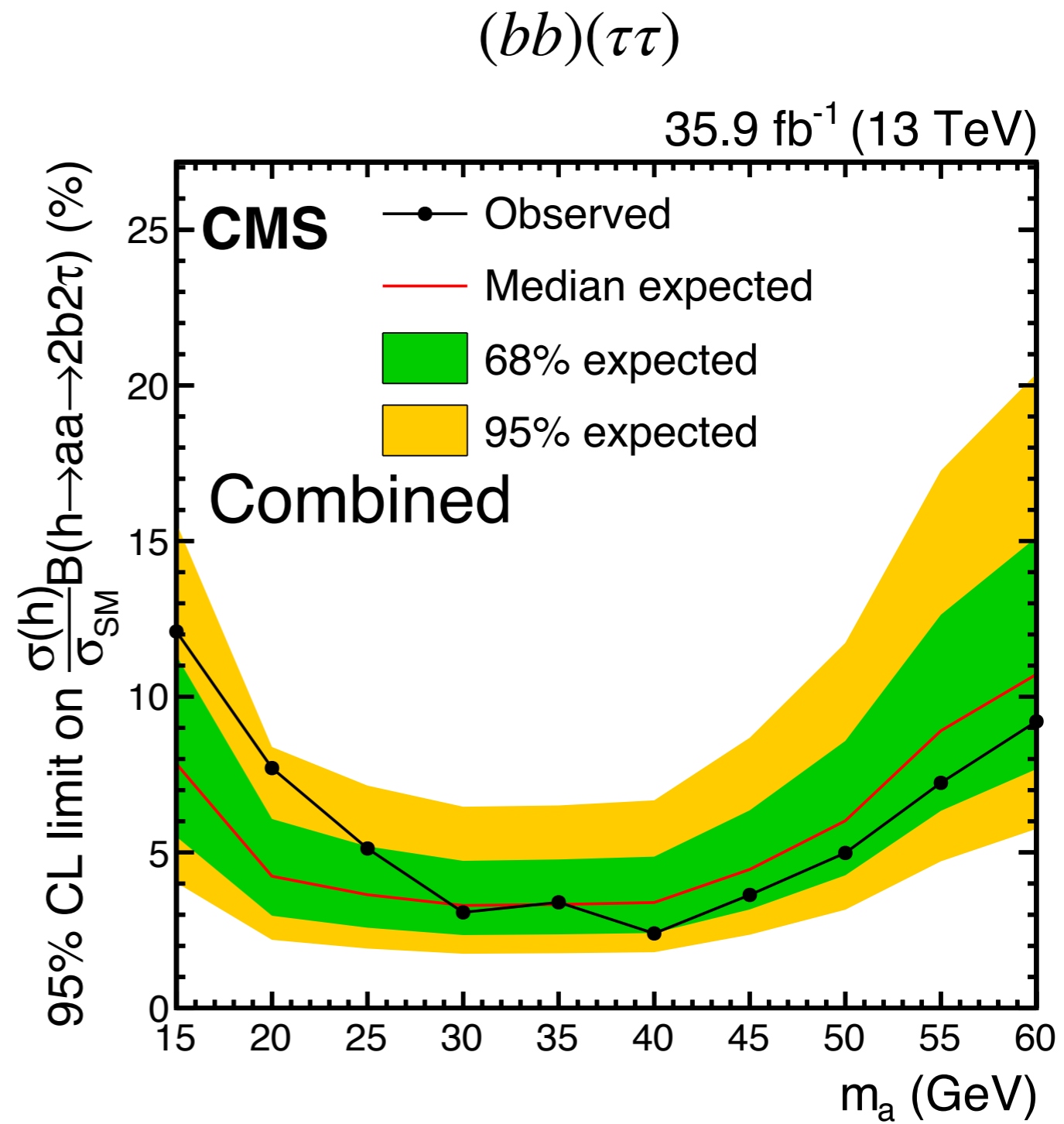
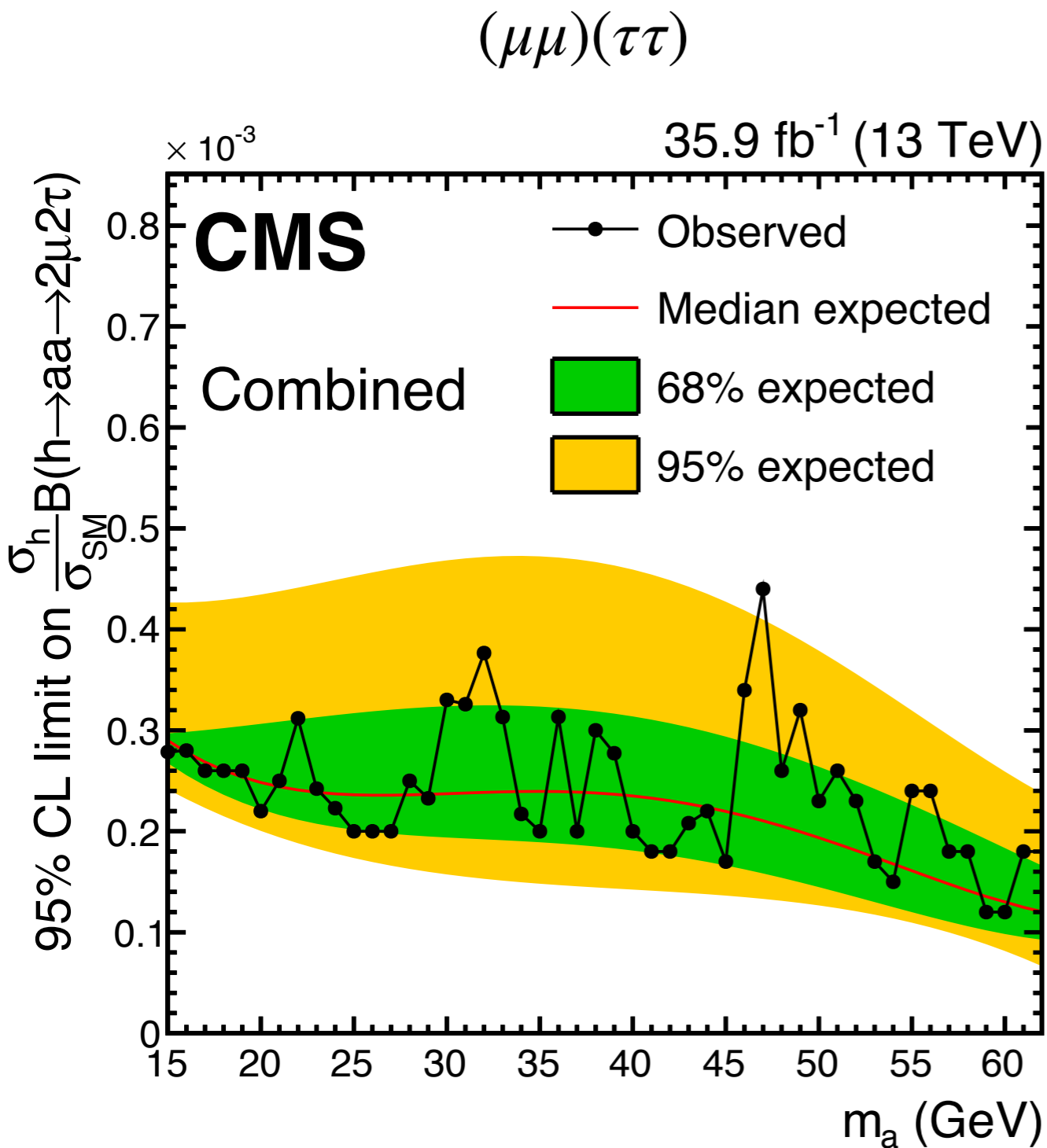
- ▶ Range:  $16 \div 60 \text{ GeV}$
- ▶ Final states:  $e\mu, \mu\tau_h, e\tau_h$
- ▶ Four different categories based on  $m_{b\tau\tau}^{\text{vis}}$
- ▶ Fake rate method for  $j \rightarrow \tau$
- ▶ Signal extracted using  $m_{\tau\tau}^{\text{vis}}$



## $(\mu\mu)(\tau\tau)$

- ▶ Range:  $16 \div 60 \text{ GeV}$
- ▶ Final states:  $(\mu\mu)(e\mu, \mu\tau_h, e\tau_h, \tau_h\tau_h)$
- ▶ Search for a peak in the di-muon spectrum
- ▶ Fake rate method for  $j \rightarrow \tau$

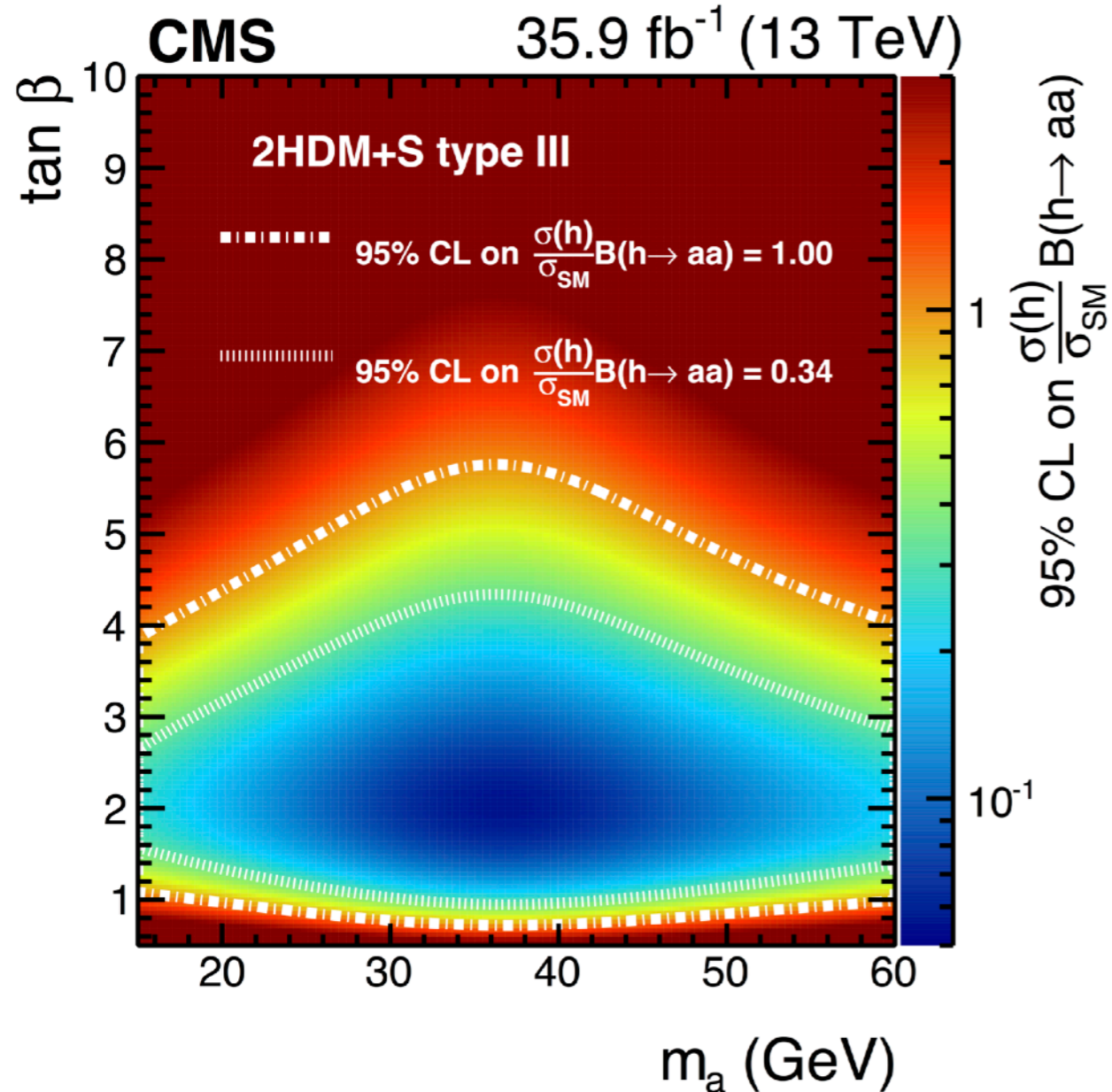
# Model Independent Limits



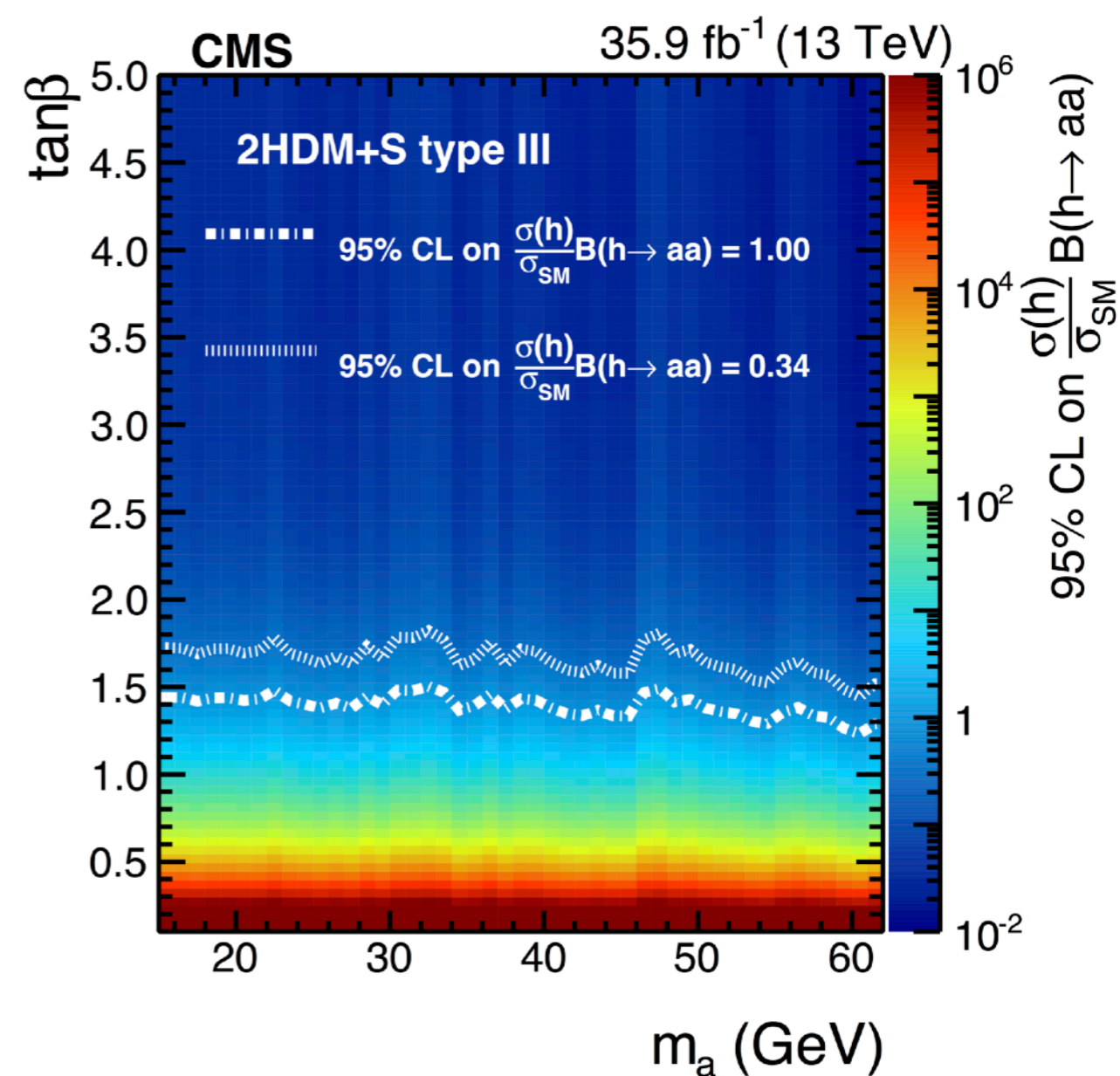
Assuming SM production xsec and mechanisms for h:  
 $12\% < BR(h \rightarrow aa \rightarrow 2\mu 2\tau) < 30\%$       $3\% < BR(h \rightarrow aa \rightarrow 2b 2\tau) < 12\%$

# Model Dependent Limits

$(bb)(\tau\tau)$



$(\mu\mu)(\tau\tau)$



Computing the branching fractions of  $a$  to SM particles

limits on  $\frac{\sigma_h}{\sigma_{SM}} BR(h \rightarrow aa)$  for different NMSSM models.

Contours correspond to exclusion for  $\frac{\sigma_h}{\sigma_{SM}} BR(h \rightarrow aa) = 1$  or  $= 0.34$

# Conclusions

# Conclusions

- ▶ Very successful start of BSM Higgs boson searches for LHC Run-2.
- ▶ Rich program of (SUSY motivated) BSM Higgs boson searches.
- ▶ Final states with tau leptons have a central role
- ▶ Both experiments ATLAS and CMS show very compatible and consistent results.
- ▶ Looking forward to analyses of the full LHC Run-2 dataset with more than 150/fb!

# Backup

Fake factors as a function of the  $\tau_h p_T$ , in categories of the  $\tau_h$  decay mode and the jet multiplicity ( $N_{\text{jet}}=0$ ,  $N_{\text{jet}}>0$ )

DR	ltau	tautau
QCD	<ul style="list-style-type: none"> <li>• tau pair Same Sign (orthogonal to SR)</li> <li>• transvers mass(lep,Emiss) &lt; 40 (reduce W+jets)</li> <li>• Relative Iso (l) [0.05,0.15]</li> </ul>	<ul style="list-style-type: none"> <li>• tau pair Same Sign (orthogonal to SR) (No need to reduce W+jets)</li> <li>• considering combinatorial effect, this background weighted with 0.5</li> </ul>
W+jets	<ul style="list-style-type: none"> <li>• transvers mass(lep,Emiss) &gt; 70 (away from SR)</li> <li>• #btag == 0 (reduce tt)</li> </ul>	<ul style="list-style-type: none"> <li>• QCD FF used for this background.</li> <li>• considering combinatorial effect, this background weighted with 1</li> </ul>
tt	<ul style="list-style-type: none"> <li>• Subdominant process</li> <li>• No sufficiently well populated DR covering a similar phase space as SR</li> <li>• MC samples, after SR selection, before categorisation, used</li> </ul>	<ul style="list-style-type: none"> <li>• QCD FF used for this background.</li> <li>• considering combinatorial effect, this background weighted with 1</li> </ul>



# MSSM H/A/h $\rightarrow \tau\tau$

ATLAS: [JHEP 01 \(2018\) 055](#)  
 CMS: [arXiv:1803.06553](#)

Model independent limits interpreted in the hMSSM and MSSM  $m^{\text{mod}+}_h$ .

Exclusion contours in the  $m_A$ - $\tan\beta$  plane

