



# Physics in Collision 2022

The 41st International Symposium on Physics in Collision

5-9 September, 2022 | Tbilisi, Georgia



## Search for Additional Higgs Bosons

*PIC, Sep 7, 2022*

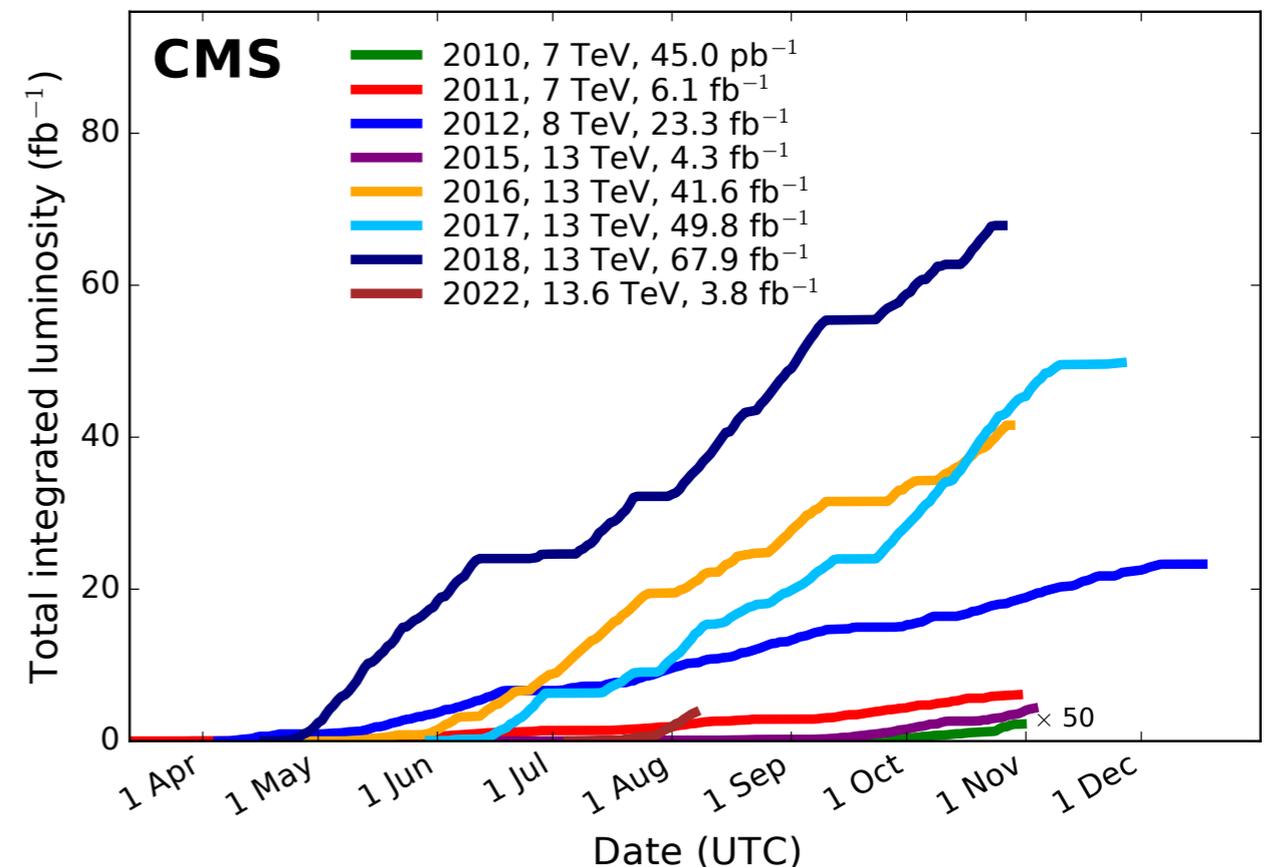
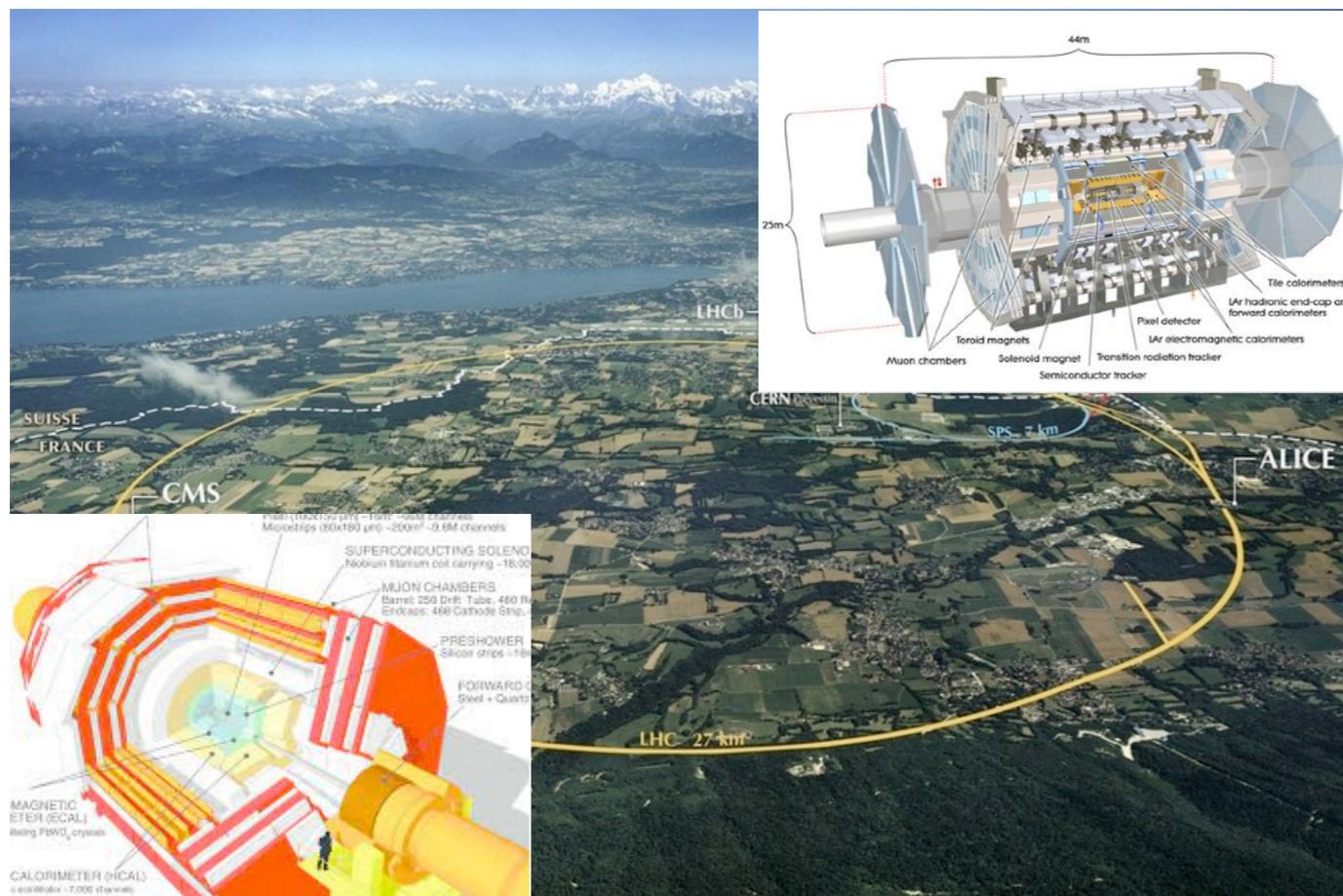


Keti Kaadze (Kansas State University)  
on behalf of the ATLAS  
and CMS Collaborations



# LHC and Detectors

- Very successful Run 1 and 2 at the LHC:  $\sqrt{s} = 8, 13$  TeV, Lumi over 150/fb
  - Remarkable performance of LHC and the experiments
- Particle physics research at the energy frontier has entered an exciting era
  - Improve precision of measurements; Have an access to rare processes; Discover some for first time observed in pp collisions; Go after many exotic signatures in Higgs sector and beyond...





10 years  
**HIGGS boson**  
discovery

Nature: ATLAS

Nature: CMS

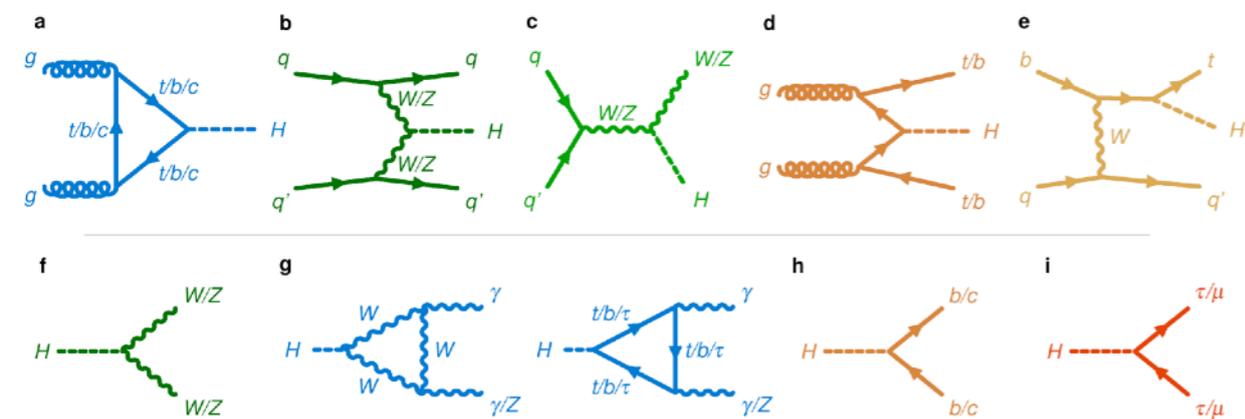
Phys. Lett. B 805 (2020) 135425

arXiv:2207.00320

# Higgs Status

Mass measurement with 1 per mille precision

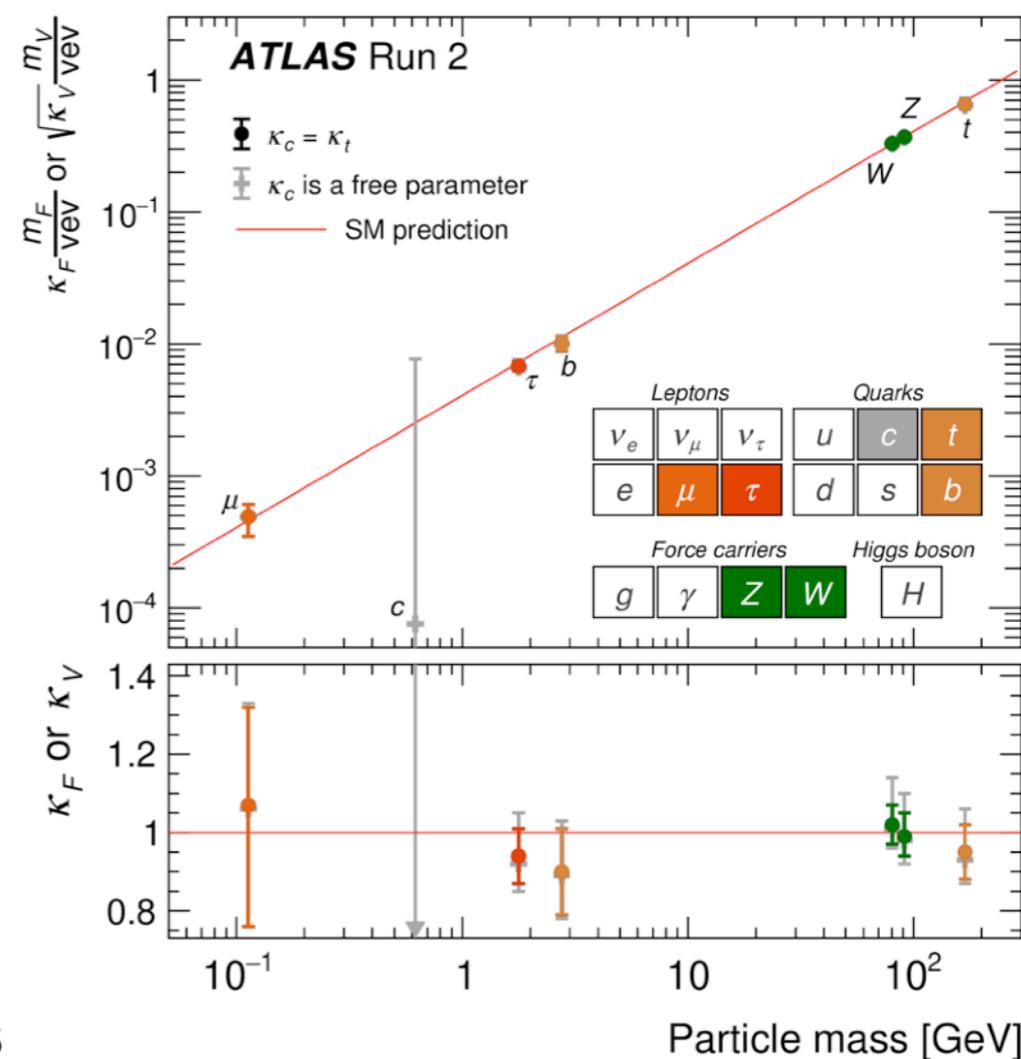
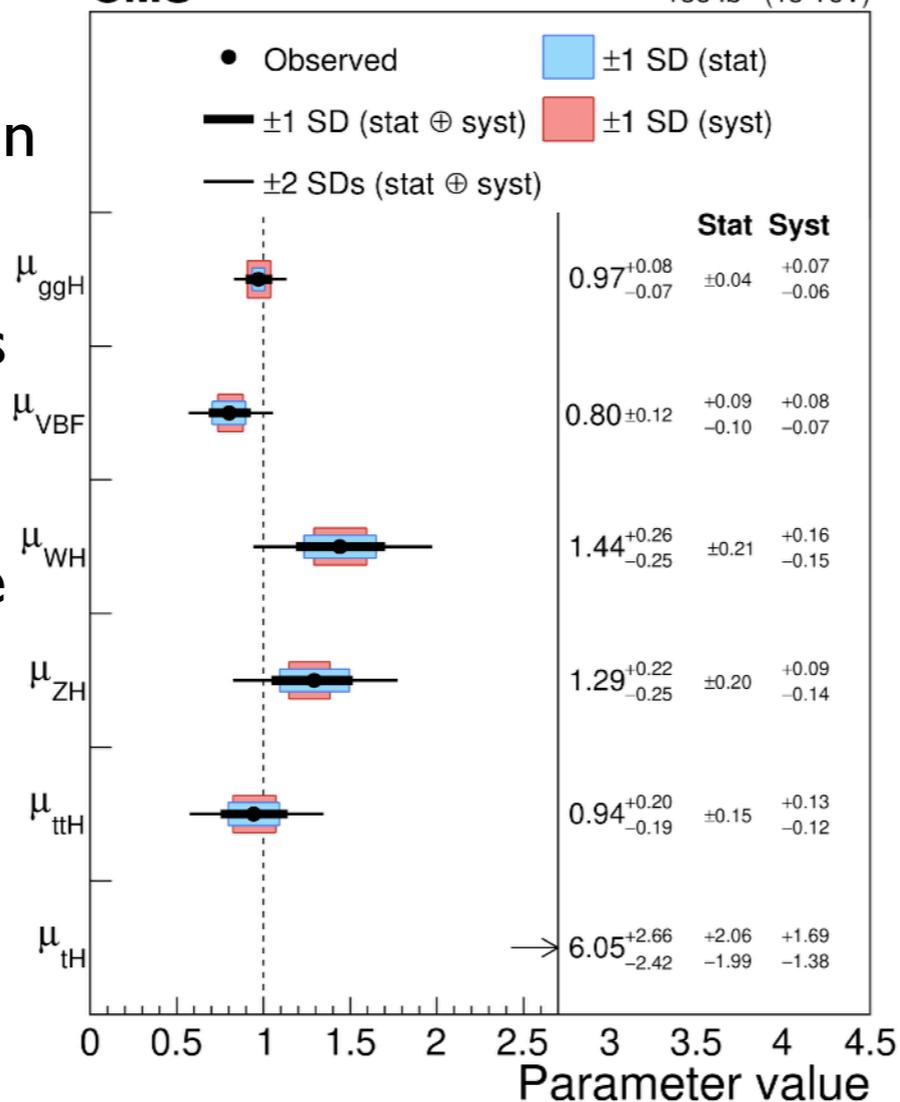
ATLAS+CMS Run1	$125.09 \pm 0.24$	( $\pm 0.21$ stat $\pm 0.11$ syst) GeV
CMS Run1 + 2016	$125.38 \pm 0.14$	( $\pm 0.11$ stat $\pm 0.08$ syst) GeV
ATLAS Run1 + <i>4l</i> Run2	$124.94 \pm 0.17$	( $\pm 0.17$ stat $\pm 0.03$ syst) GeV



- Observation of all main production processes
- Observation of decays to bosons and third-generation fermions and evidence of decay to  $\mu\mu$

CMS

138 fb<sup>-1</sup> (13 TeV)





# Additional Higgs?

- So far, the observed H(125) boson is consistent with the SM predictions. But...
- Observed phenomena (dark matter, neutrino masses, matter-anti matter asymmetry, etc.), hierarchy problem, can be explained by theories beyond the SM
- The new physics can manifest in the Higgs sector
  - Deviations in measurements of the H(125) properties from the SM
  - Exotic decay modes of the H(125) boson
  - Existence of additional neutral or charged scalar bosons



# Extended Higgs Sector

- Minimal extensions Two-Higgs Doublet Model (2HDM): CP-even  $h$  and  $H$ , CP-odd  $A$ , Singly charged  $H^\pm$
- 2HDM with additional singlet (2HDM+S) leads to two additional neutral Higgs CP-even  $h$  and  $H$ , CP-odd  $A$ ,  $h_s, A_s$ , Singly charged  $H^\pm$
- Higgs Triplet Models (HTMs) extend the sector by additional scalar triplet: Presence of doubly-charged Higgs bosons  $H^{\pm\pm}$

$$\begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \Rightarrow H_{\text{SM}}$$

$$\begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix} + \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix} \Rightarrow h, H, A, H^\pm$$

$$\begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix} + \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix} + s \Rightarrow h_{(1,2,3)}, a_{(1,2)}, h^\pm$$

- In this talk — the latest results on searches for additional Higgs bosons

- Light neutral Higgs bosons
- Heavy neutral Higgs bosons
- Charged Higgs bosons

## 2HDM

type I All quarks & leptons couple to  $\Phi_2$

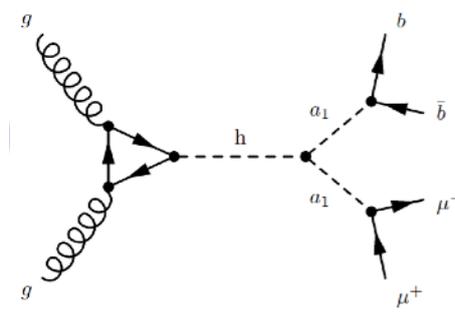
type II All  $u$ -type to  $\Phi_2$  and all  $d$ -type &  $\ell$  to  $\Phi_1$

type X Both  $u$  &  $d$  types couple to  $\Phi_2$ , all  $\ell$  to  $\Phi_1$

type Y Roles of two doublets reversed wrt type II

Type	$u$	$d$	$\ell$
I	$\Phi_2$	$\Phi_2$	$\Phi_2$
II	$\Phi_2$	$\Phi_1$	$\Phi_1$
III (X)	$\Phi_2$	$\Phi_2$	$\Phi_1$
IV (Y)	$\Phi_2$	$\Phi_1$	$\Phi_2$

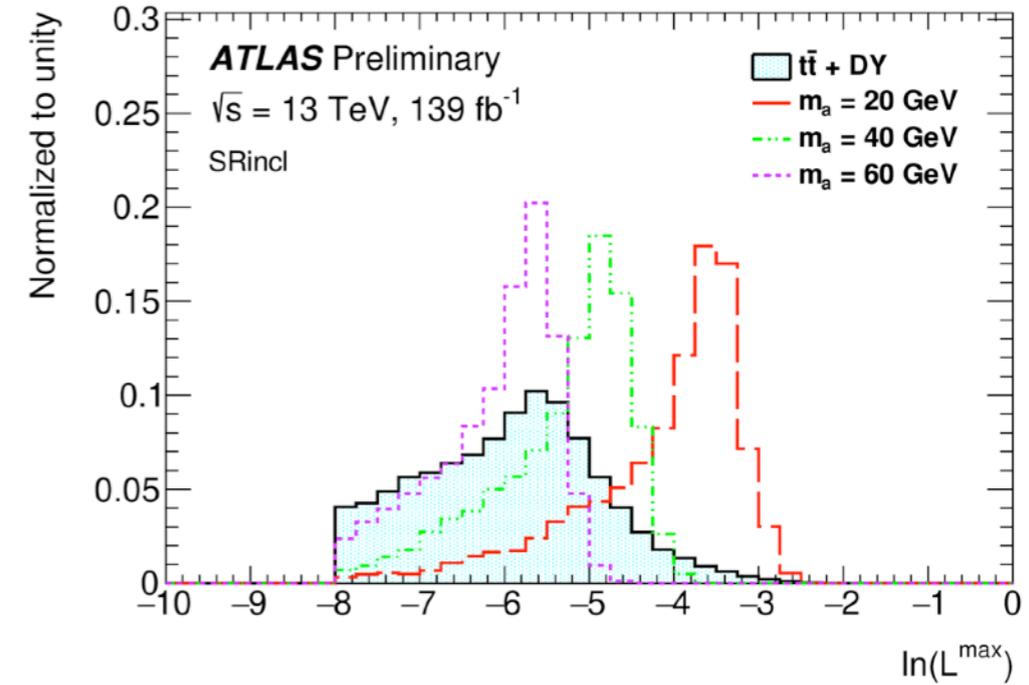
# $H \rightarrow aa \rightarrow \mu\mu bb$



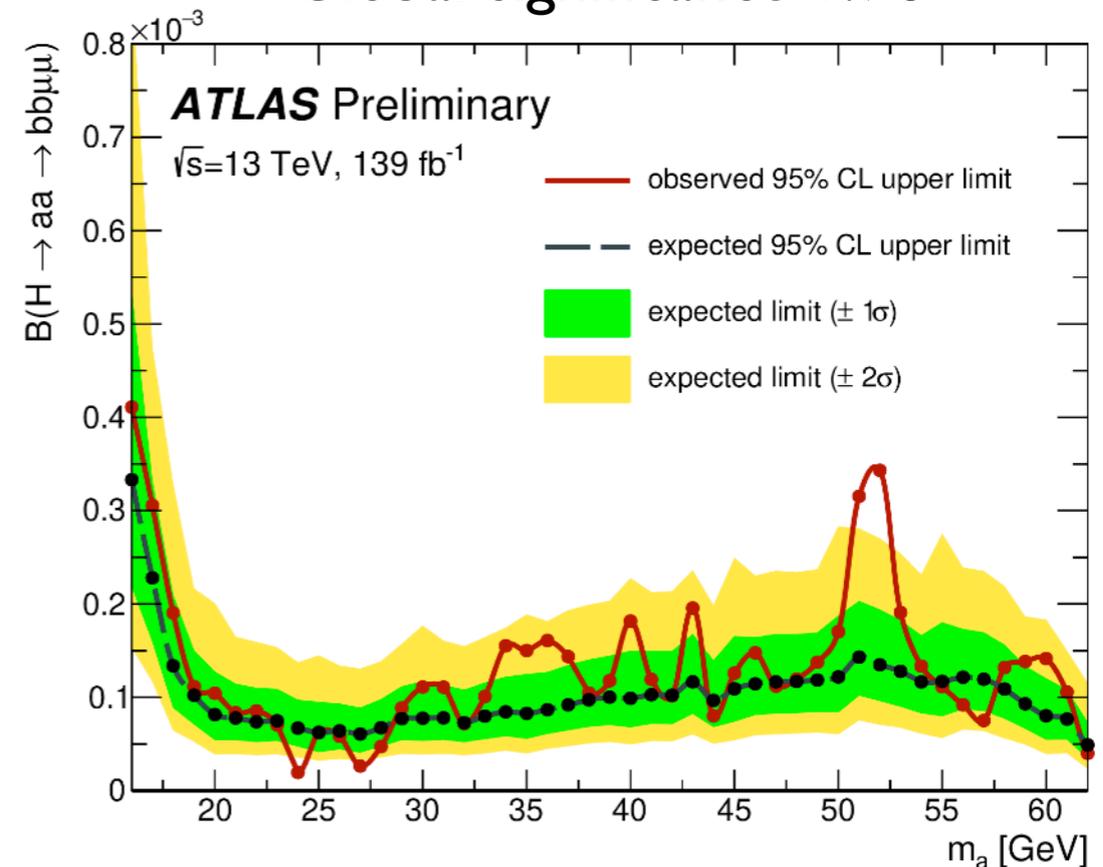
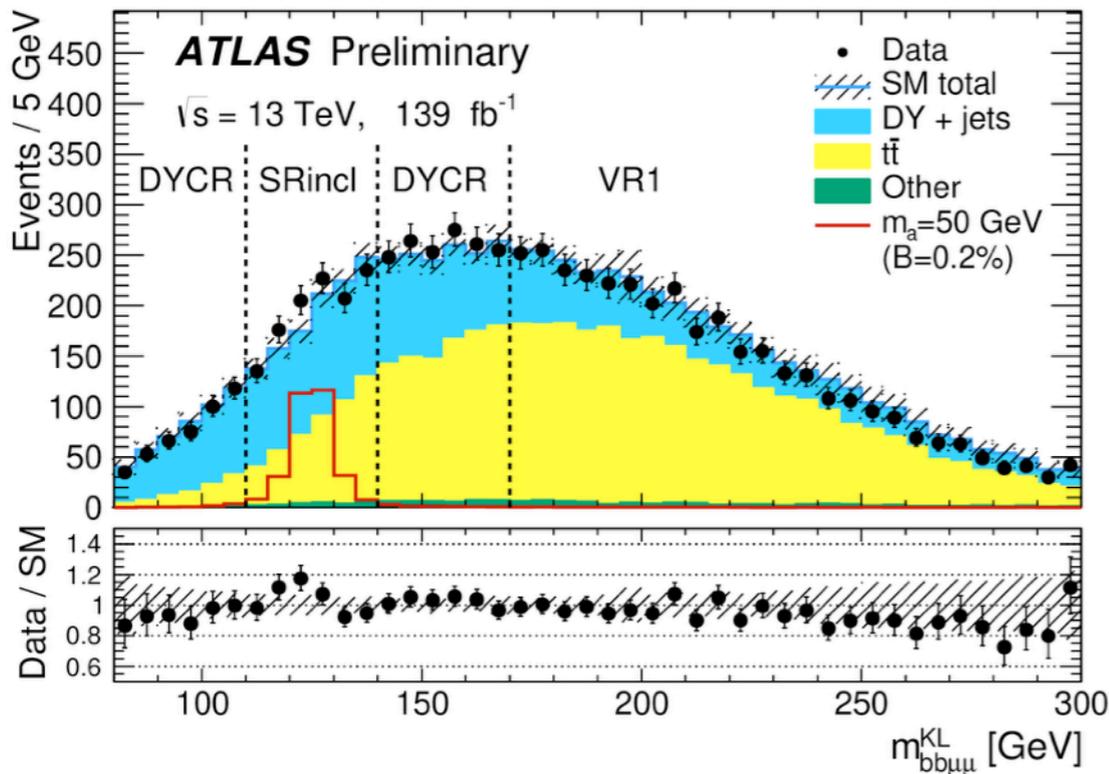
- Couplings of a boson is proportional to mass -  $\mu\mu bb$  final state balances high purity and high rate
- Using kinematic likelihood fit to improve  $m_{\mu\mu bb}$  and reduce background. Fit maximizes likelihood by shifting the b-jet energy within resolution to satisfy constraint  $m_{\mu\mu} \approx m_{bb}$ .

Sig.R.  $110 < m_{\mu\mu bb}^{KL} < 140$  GeV,  $\ln(L^{max}) > -8$ ,  $15 < m_{\mu\mu} < 65$  GeV

$16 \text{ GeV} < m_a < 62 \text{ GeV}$



Global significance  $1.7\sigma$





# $H \rightarrow aa \rightarrow 4\gamma$

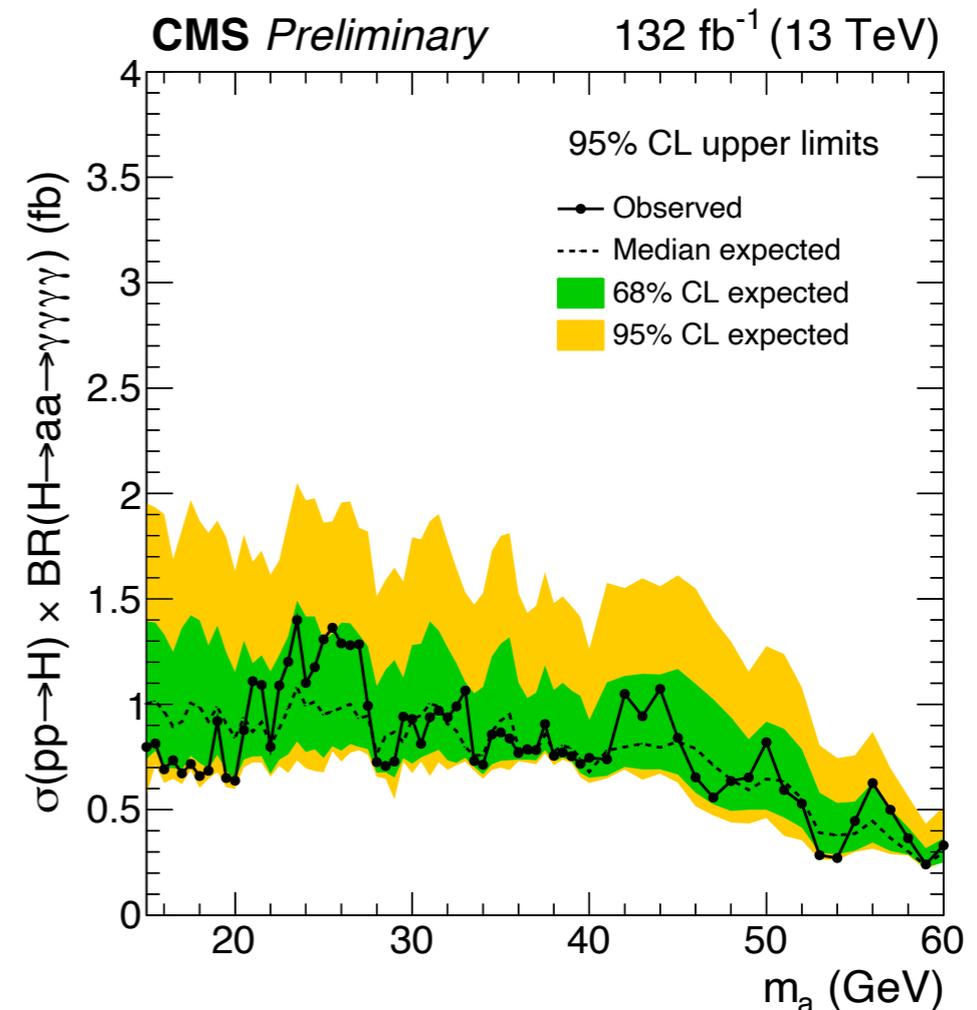
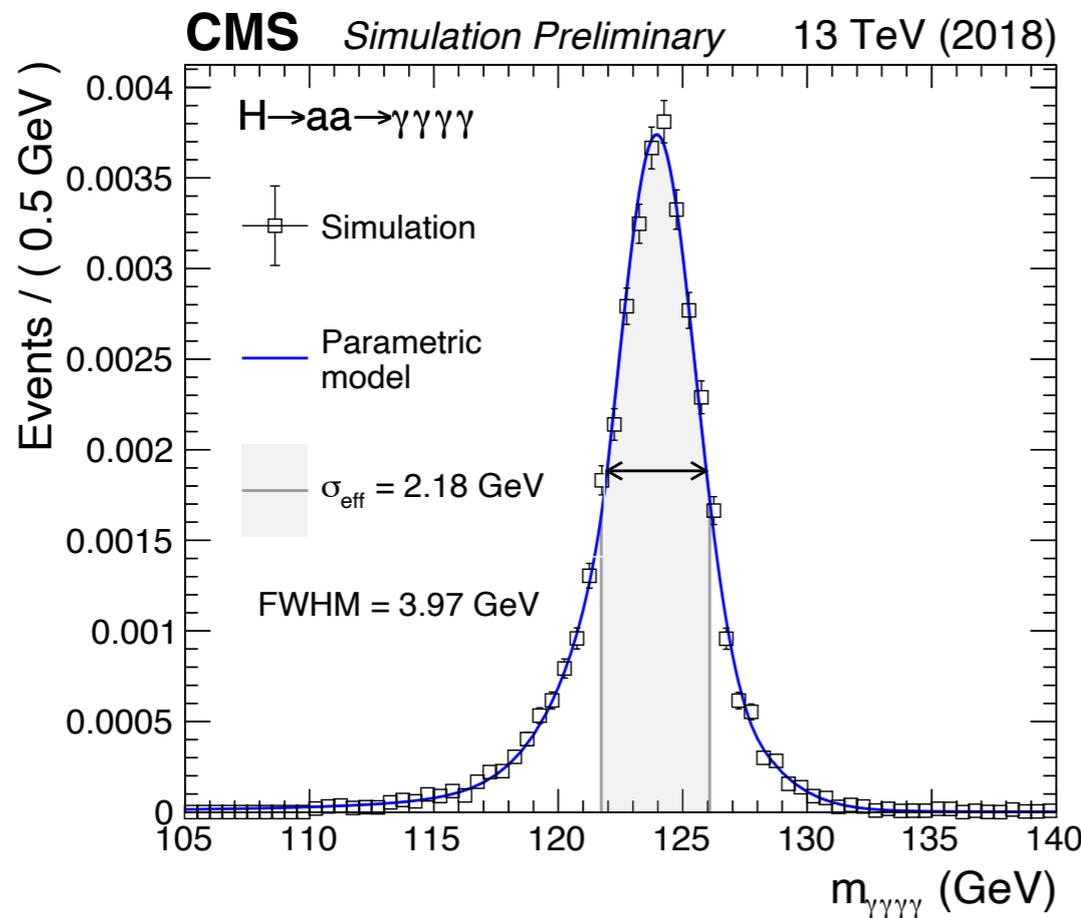
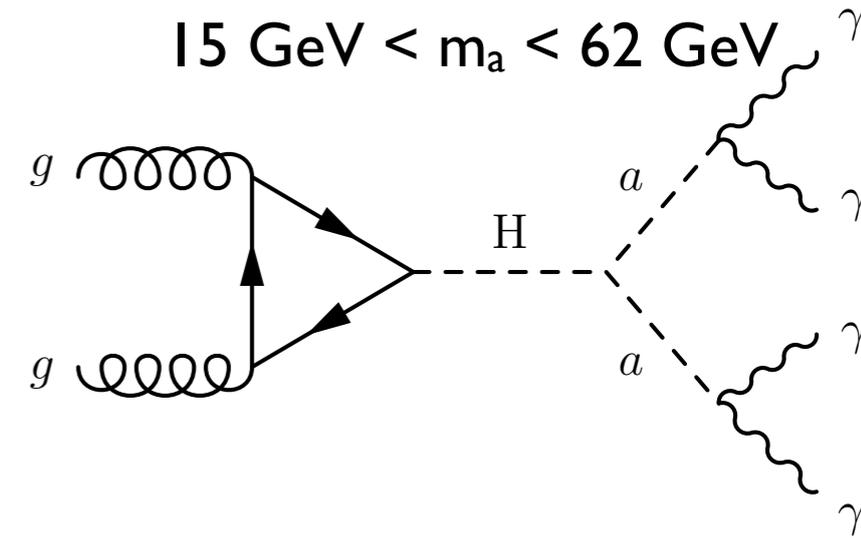
- Model independent analysis with four fully resolved photons

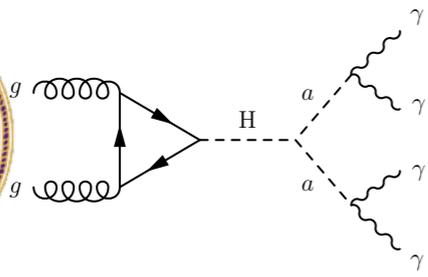
- Using BTD to separate signal and background

- photon identification,  $p_T(a)$ , smallest  $\Delta m_{a1a2}, \Delta R_{a1,..}$

- Fit data, signal, background in range  $110 < m_{\gamma\gamma\gamma\gamma} < 180$  GeV

- Signal model of  $m_{\gamma\gamma\gamma\gamma}$  with double-sided CB function; Granularity of 0.5 GeV for  $m_a < 40$  GeV (1 GeV for  $m_a > 40$  GeV);

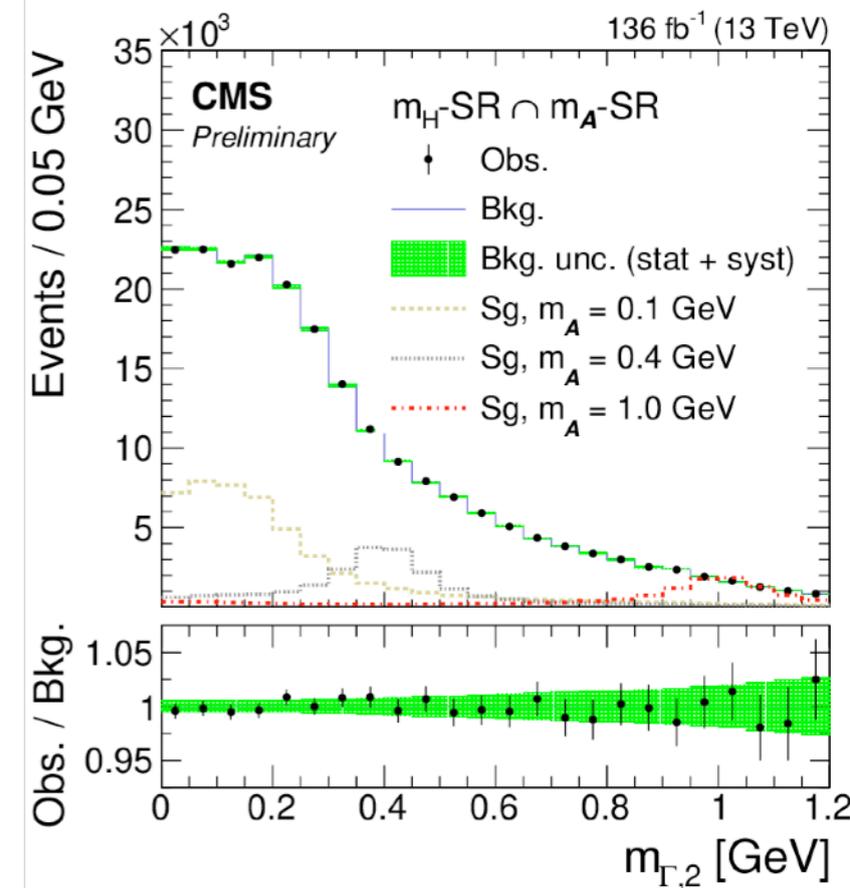
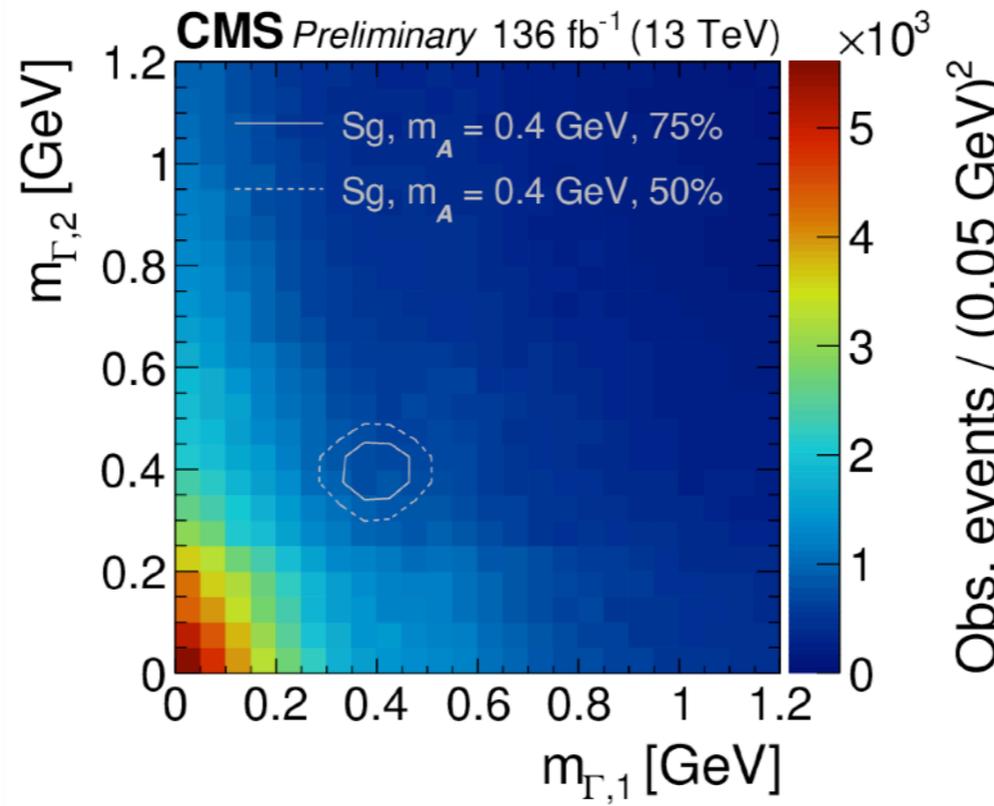
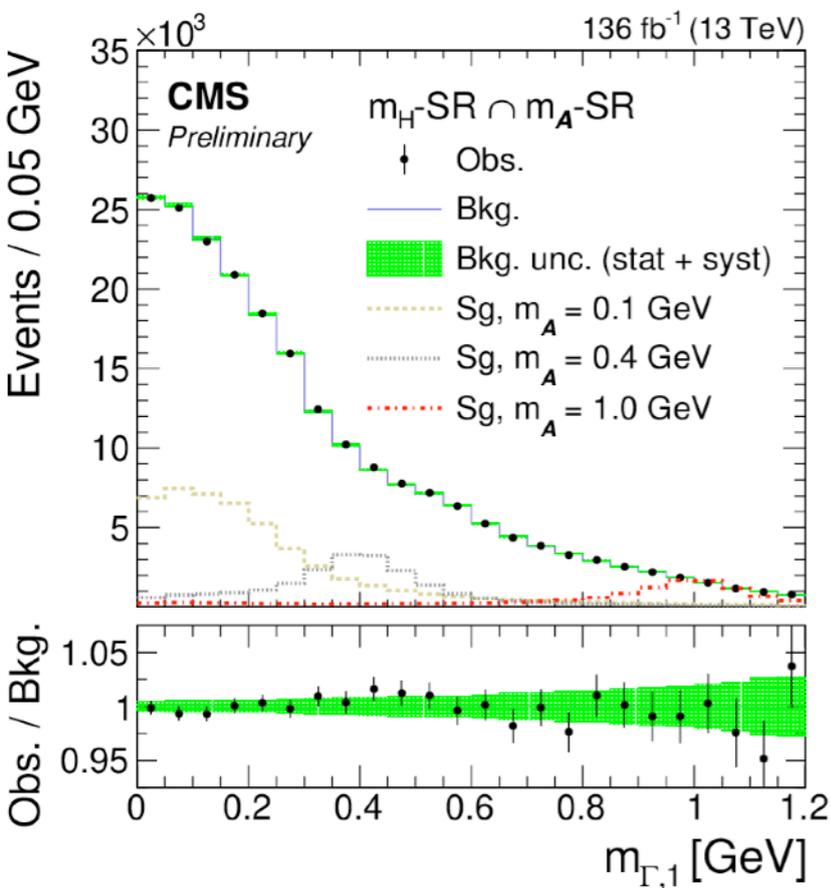
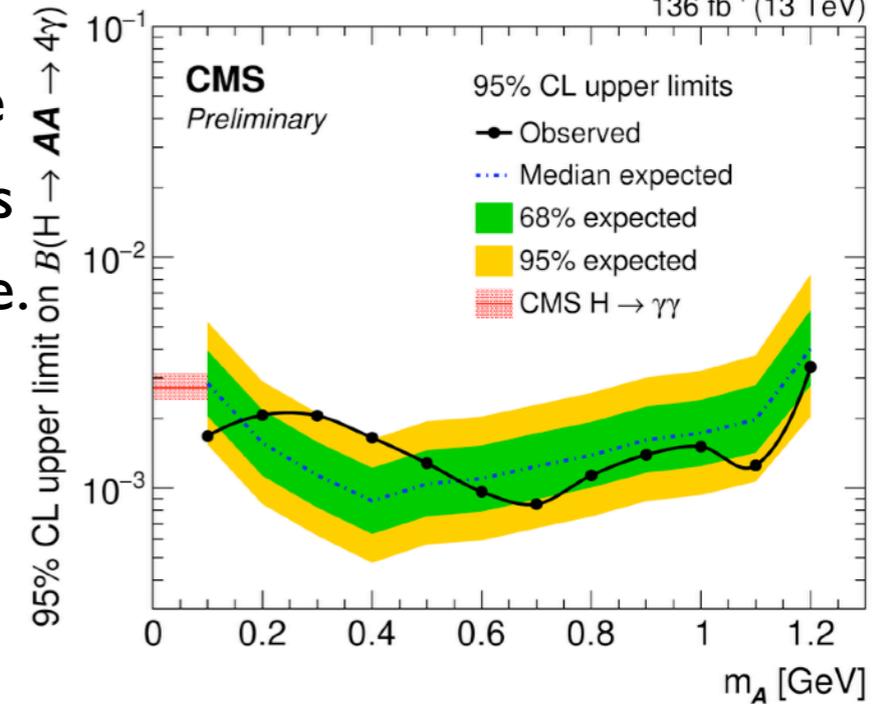




# H → aa → 4γ, very low m<sub>a</sub>

0.1 GeV < m<sub>a</sub> < 1.2 GeV

- Very different phase space; γγ merged into one photon candidate
  - Develop a dedicated convolutional NN to reconstruct γγ mass based on energy deposition in η-φ space; Validate on π<sup>0</sup> candidate.
- Use MLE to determine compatibility of observed template with signal and bkg. models
  - Signal template: 2D diagonal from simulation
  - background: binned 2D template from SM H → γγ simulation and data using sideband of di-γ mass.





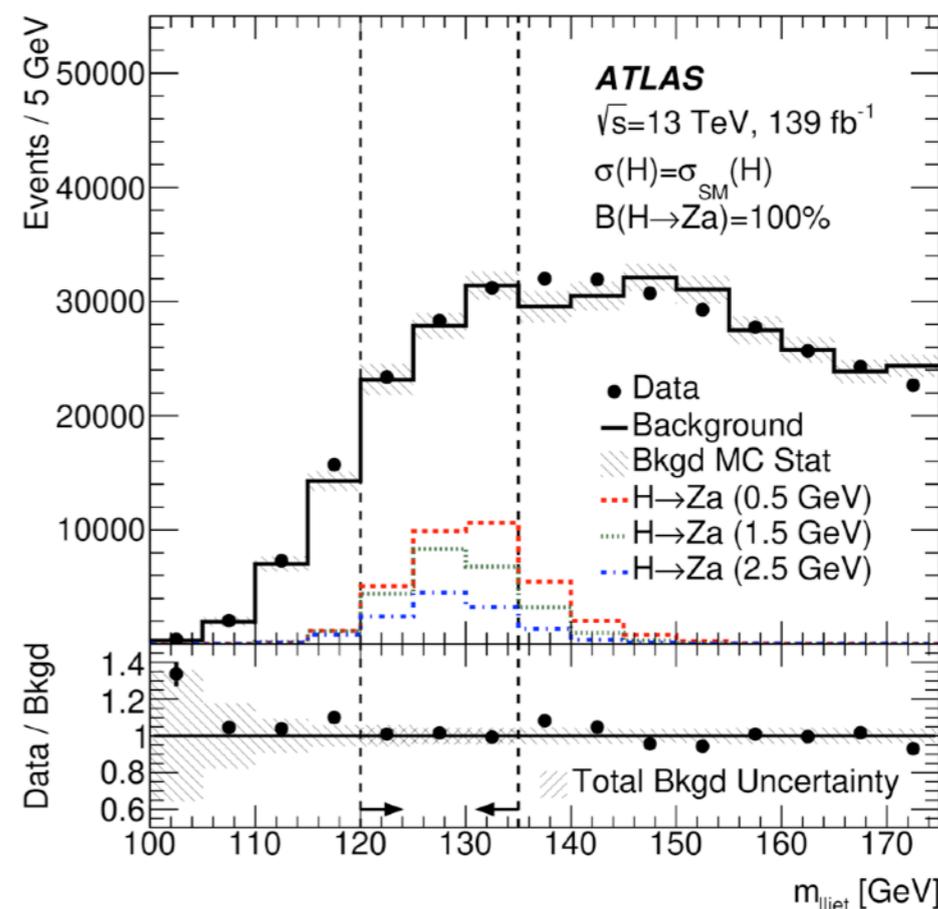
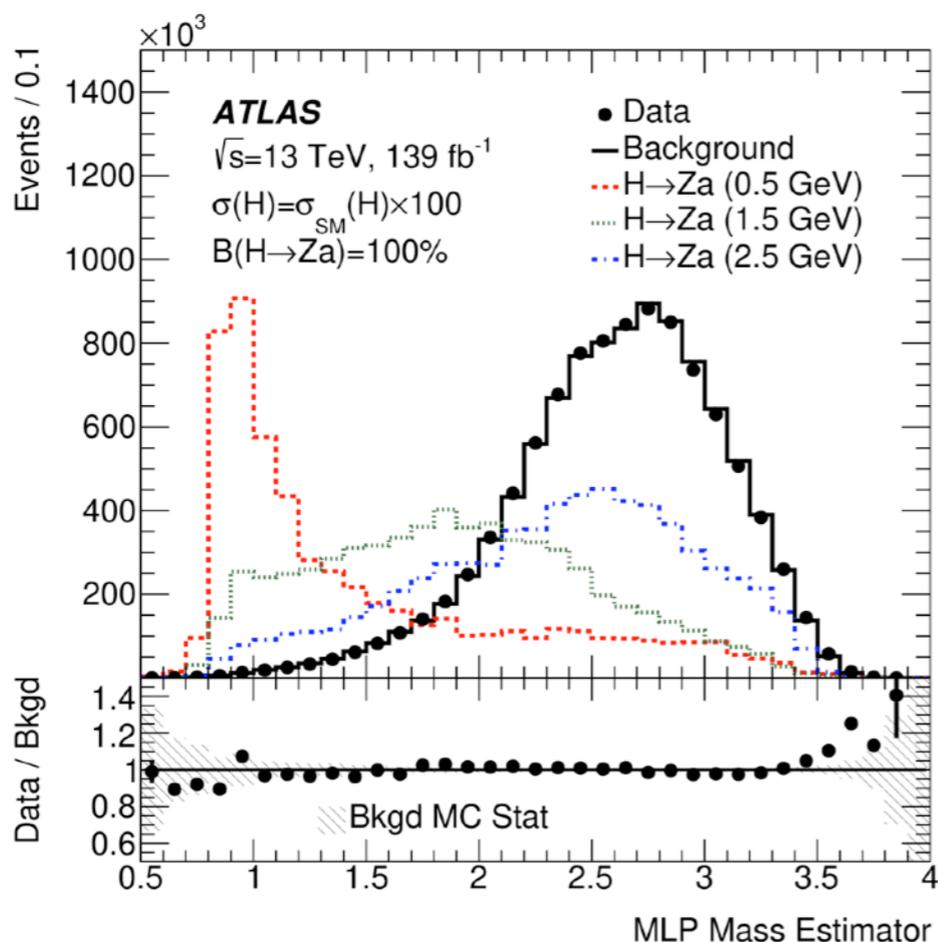
# H → Za → ℓℓ + hadrons

Limits on  $\sigma(pp \rightarrow H)Br(H \rightarrow Za)$

$a$ mass [GeV]	$a \rightarrow gg$		$a \rightarrow s\bar{s}$	
	Exp	Obs	Exp	Obs
0.5	$16^{+6}_{-5}$	17		
0.75	$19^{+7}_{-5}$	20		
1.0	$17^{+7}_{-5}$	18		
1.5	$20^{+8}_{-6}$	22	$19^{+7}_{-5}$	20
2.0	$26^{+10}_{-7}$	27	$23^{+9}_{-6}$	24
2.5	$38^{+15}_{-11}$	40	$32^{+12}_{-9}$	33
3.0	$75^{+29}_{-21}$	78	$65^{+25}_{-18}$	68
3.5	$110^{+40}_{-30}$	120		
4.0	$320^{+130}_{-90}$	340		

- Motivated from extended Higgs sector, DM, — couplings to down-type quarks suppressed
  - The same final state expected from  $H \rightarrow ZJ/\Psi$ ,  $H \rightarrow Z\eta_c$  processes handles to probe Higgs-charm coupling
- Hadronic resonance is highly boosted - using jet sub-structure variables and multilayer perceptron (MLP) classifier

$m_a < 4$  GeV

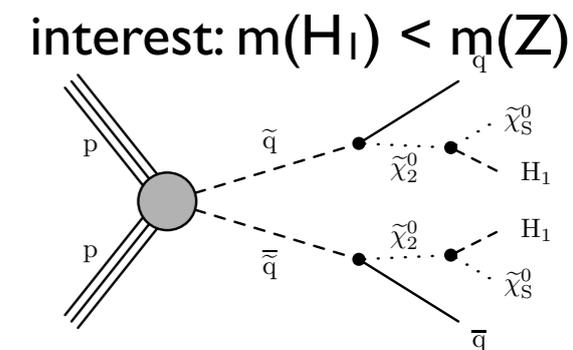




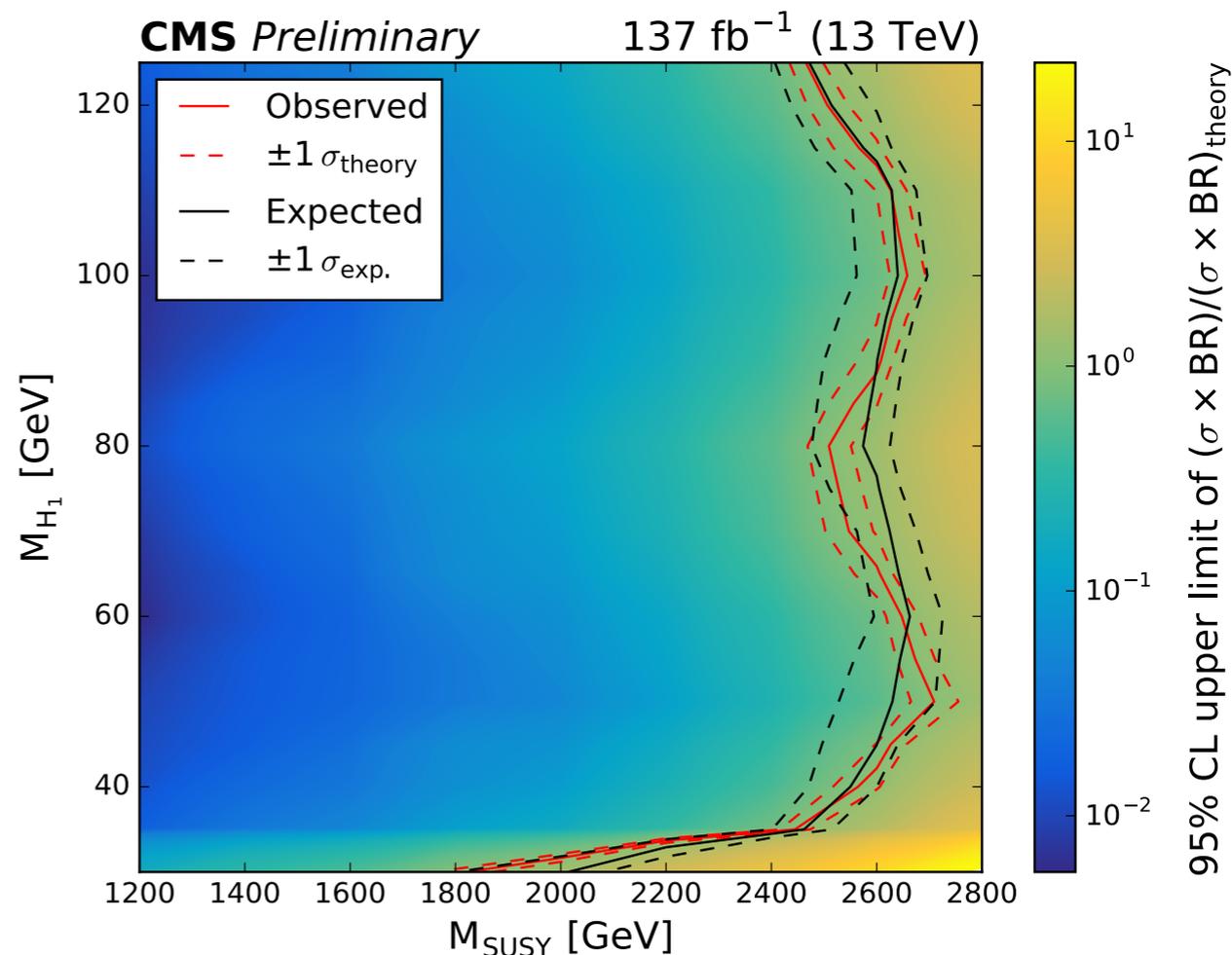
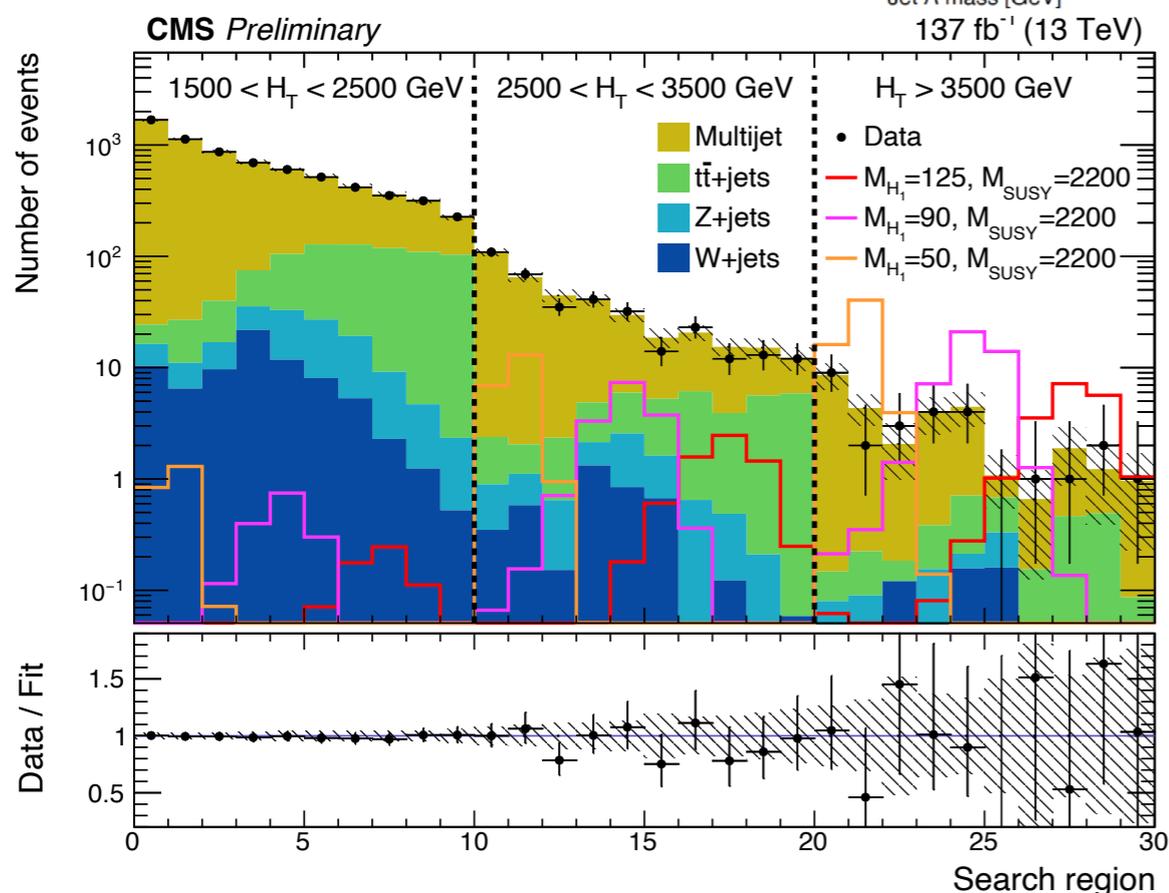
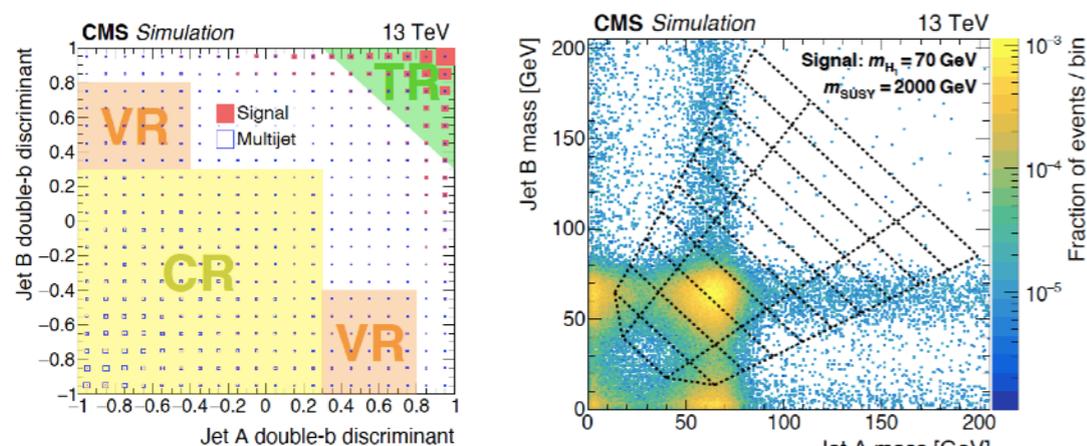
# Higgs in SUSY Cascade Decays

- NMSSM with the singlino-like neutralino ( $\chi_s^0$ ) as LSP

- $\chi_s^0$  has small coupling to other SUSY particles results;  $m(\chi_s^0) \ll m(H_1)$  results in MET suppressed scenario

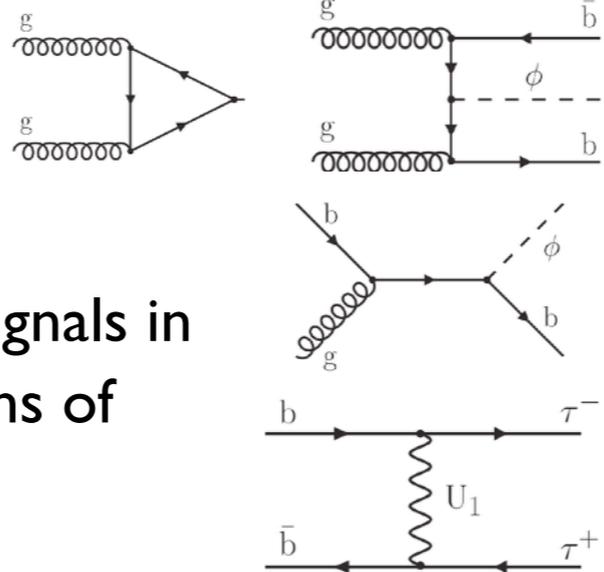


- Pair of boosted light Higgs boson  $H_1 \rightarrow bb$ : AK8 jets passing double-b-tag discriminator



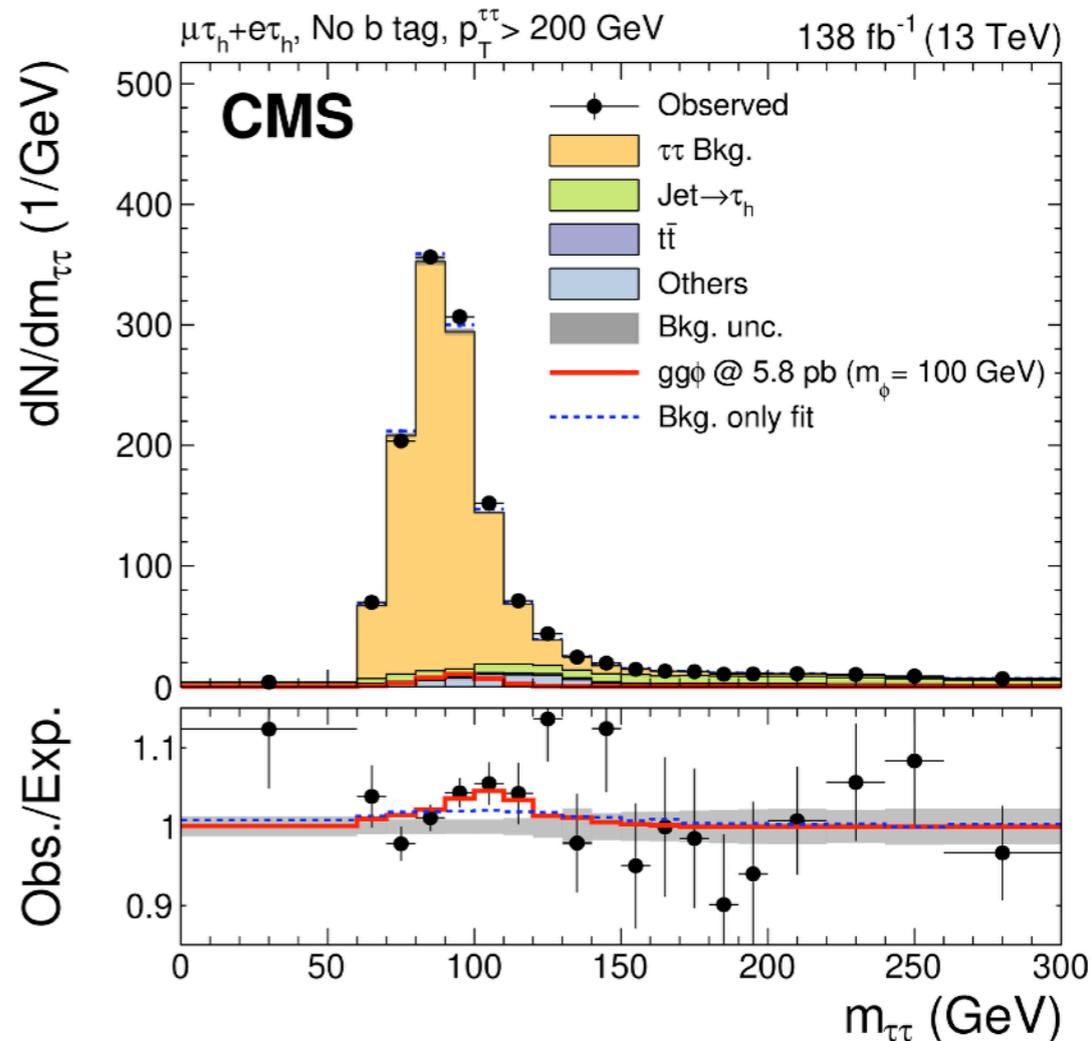
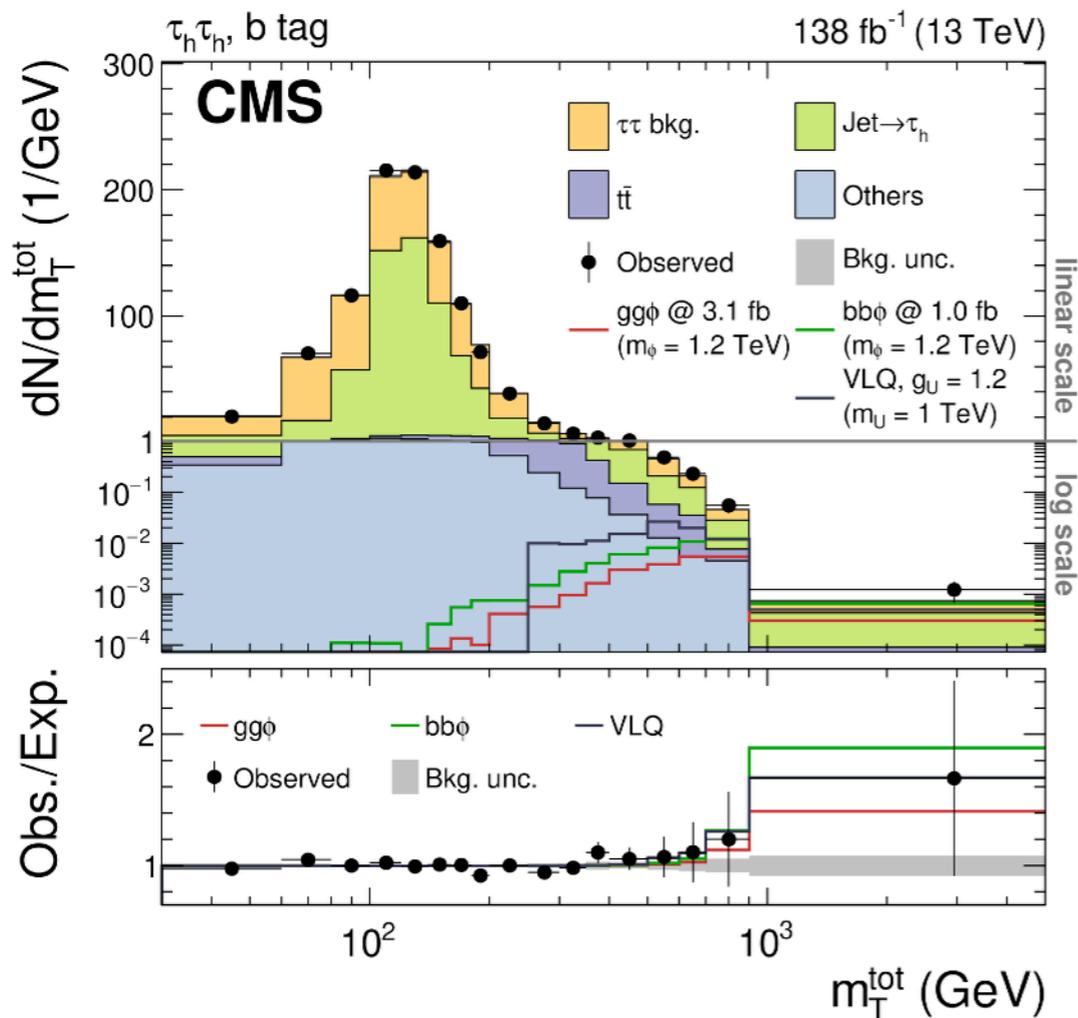
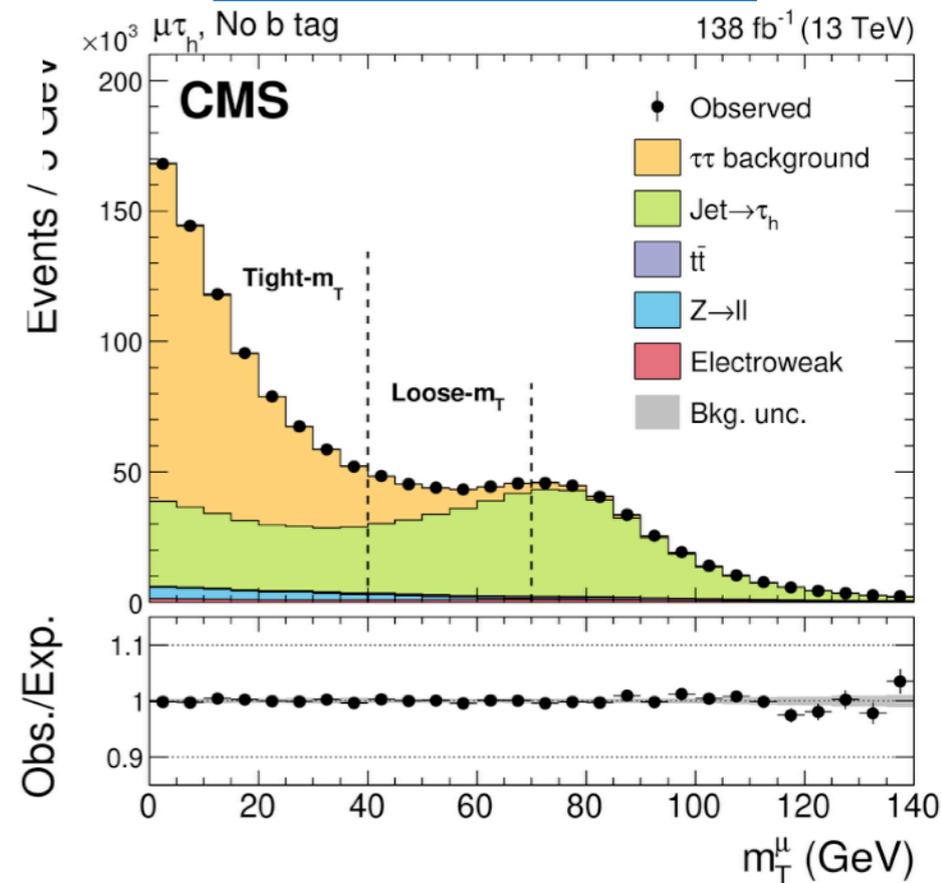
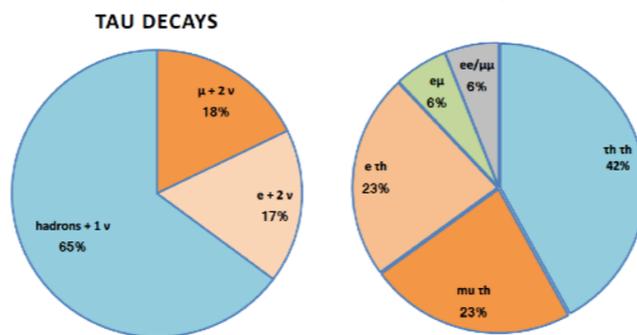


# BSM $H \rightarrow \tau\tau$



- Improved strategy to search for BSM signals in di- $\tau$  spectrum:  $gg\phi$ ,  $bb\phi$ ,  $b\phi$  productions of scalar boson; vector leptoquark

- Multiple channels, multiple categories depending on production and low/high mass ranges Dedicated observable for high/low mass search

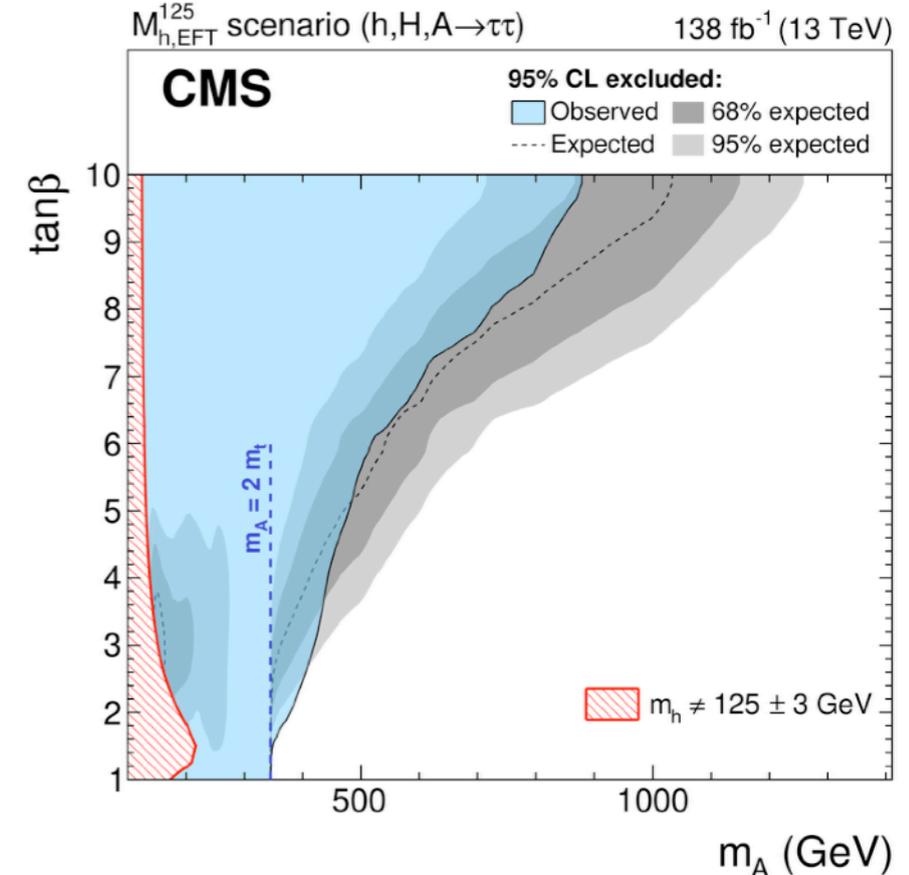
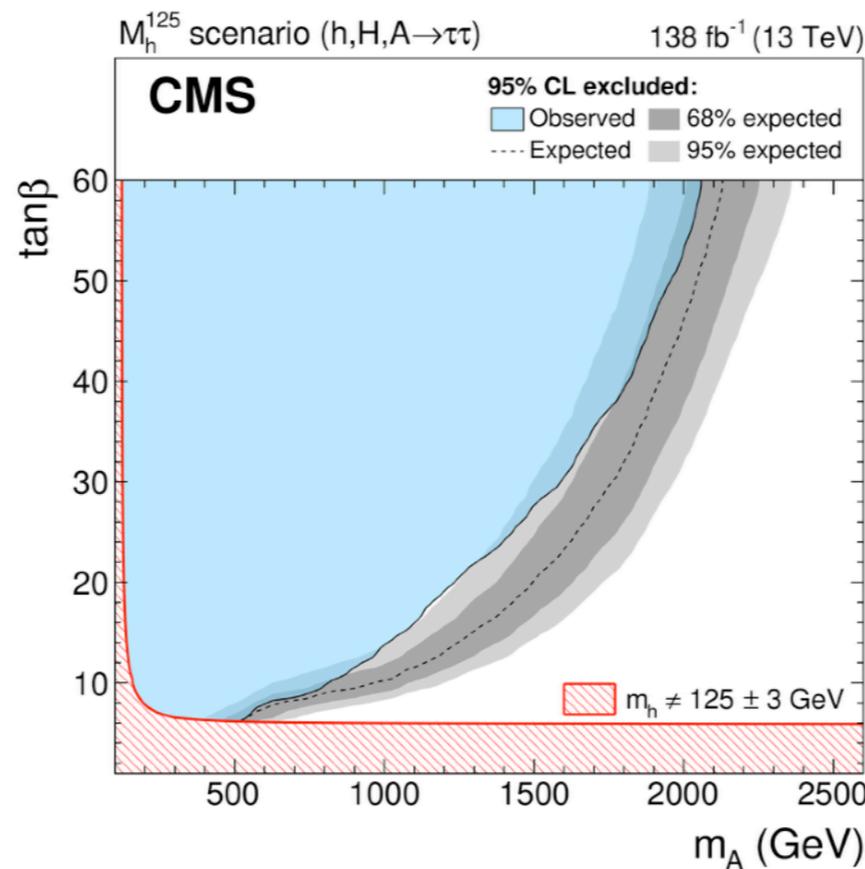
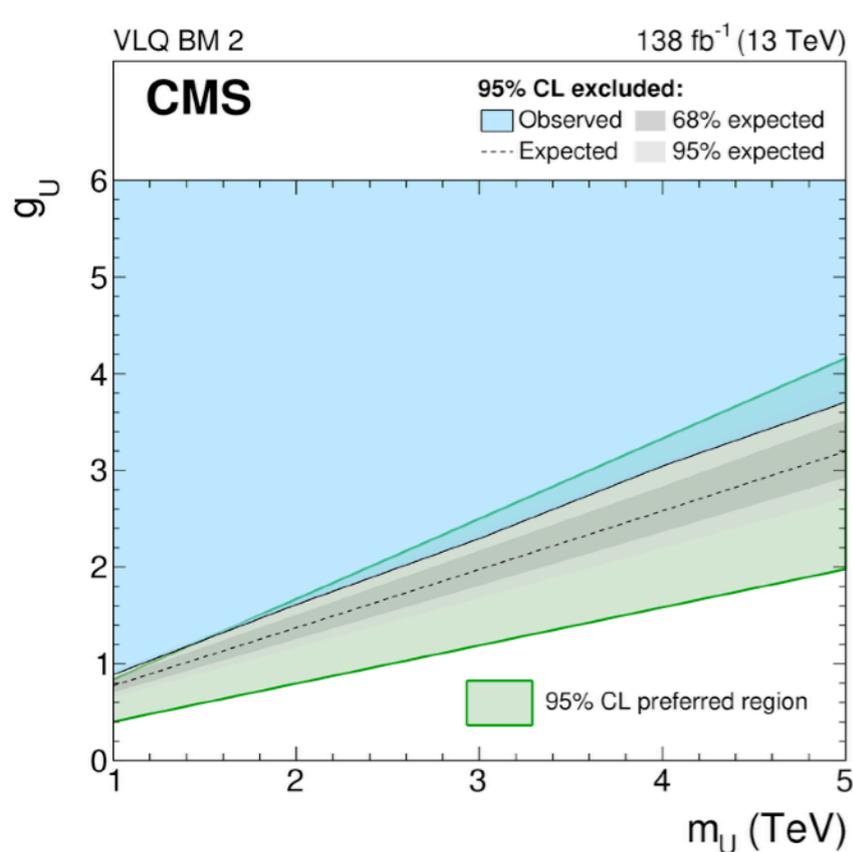
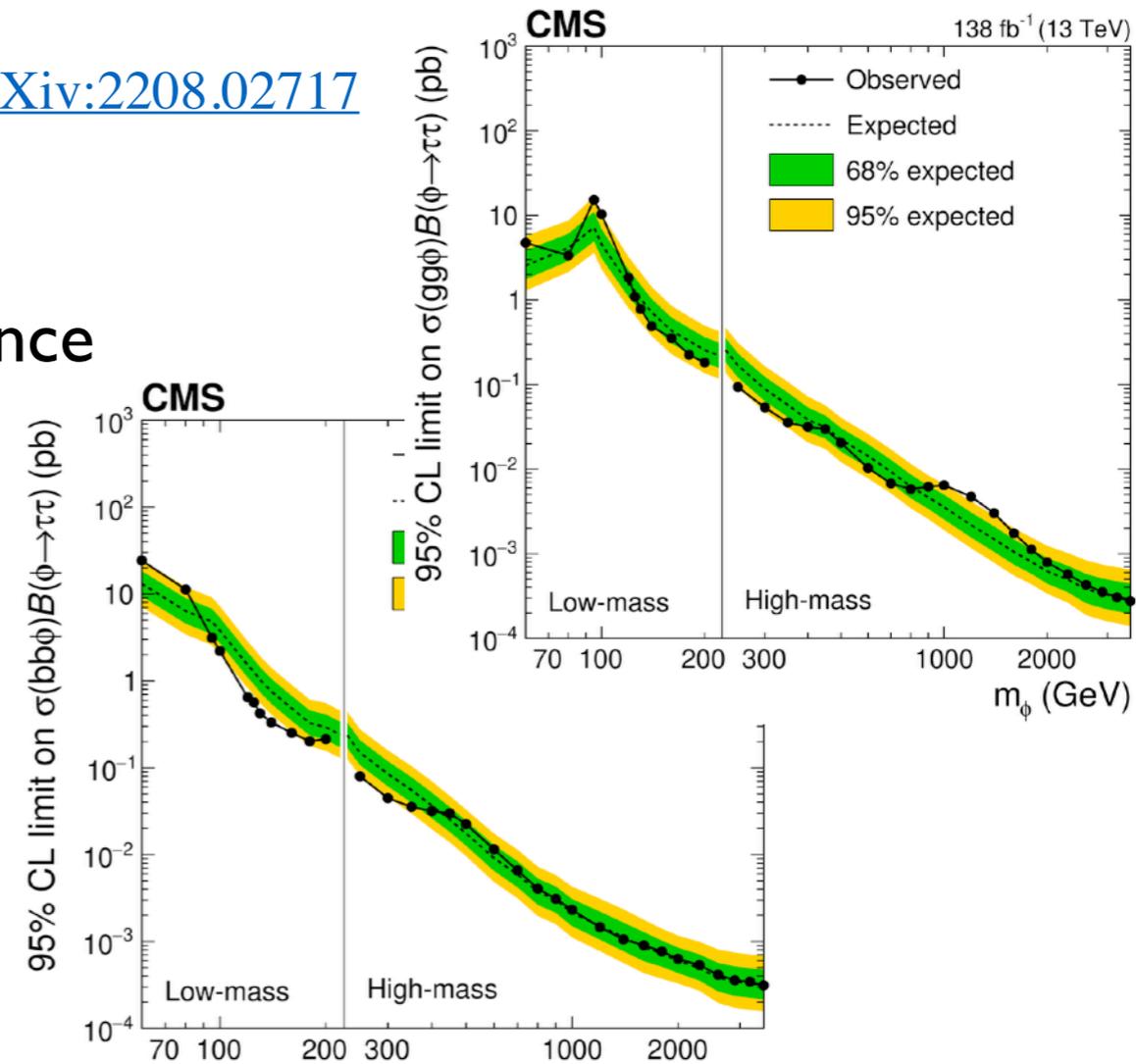




# BSM $H \rightarrow \tau\tau$

CMS arXiv:2208.02717

- Model-independent search for spin-0  $\phi$  resonance via  $gg\phi$  and  $bb\phi$  productions
- Narrow resonance with SM-like  $p_T$  spectrum and top/bottom relative contribution in  $gg\phi$  loop
- VLQ search
- MSSM three neutral Higgs boson

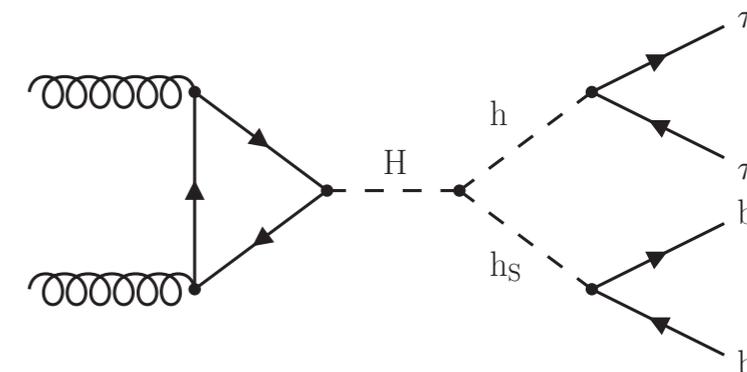




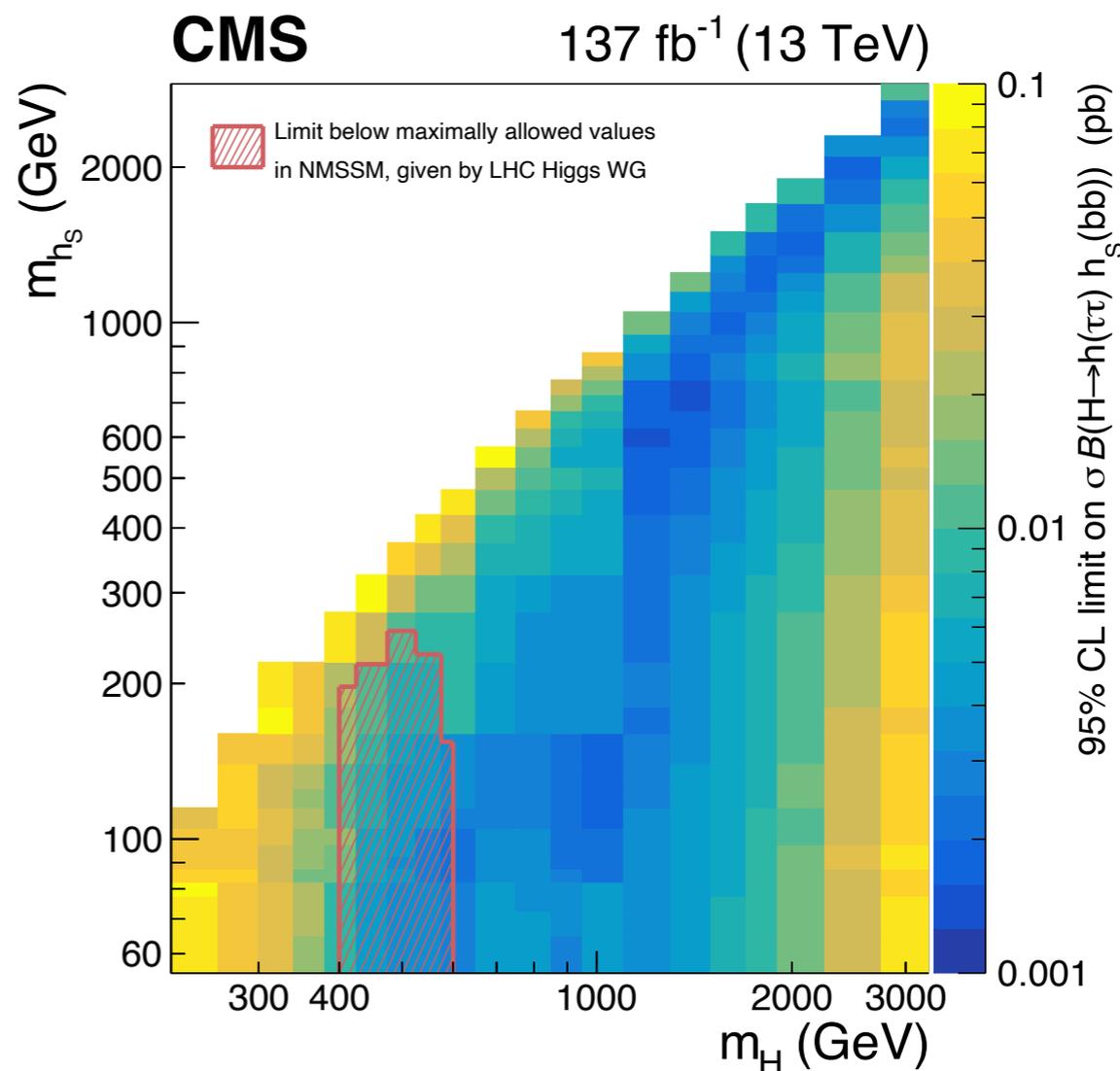
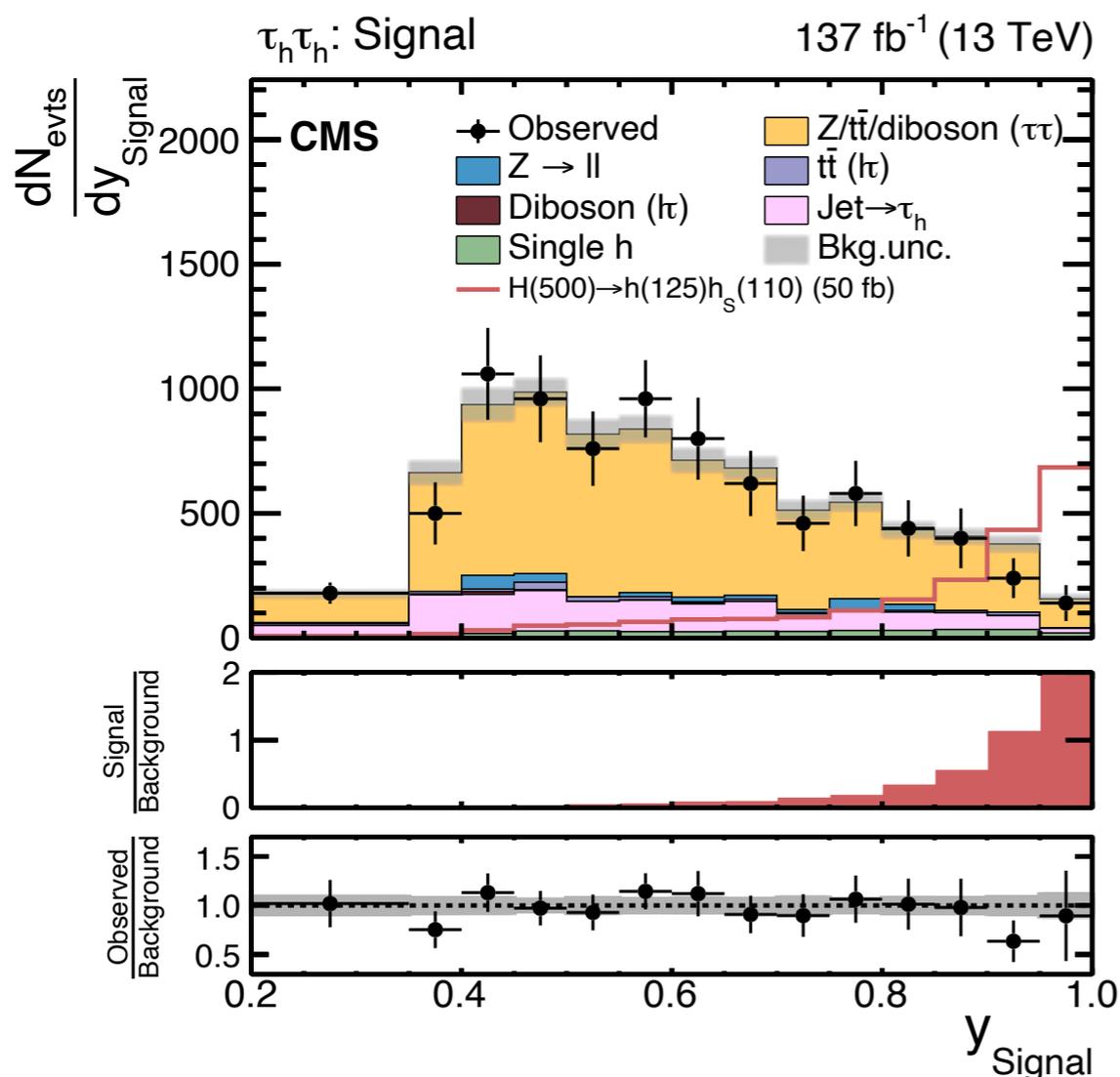
# More of BSM $H \rightarrow \tau\tau$

- NMSSM with five neutral and two charged Higgs bosons

- $h = H_{SM}, 240 \text{ GeV} \leq m_H \leq 3000 \text{ GeV},$   
 $60 \text{ GeV} \leq m_{h_s} \leq 2800 \text{ GeV}$



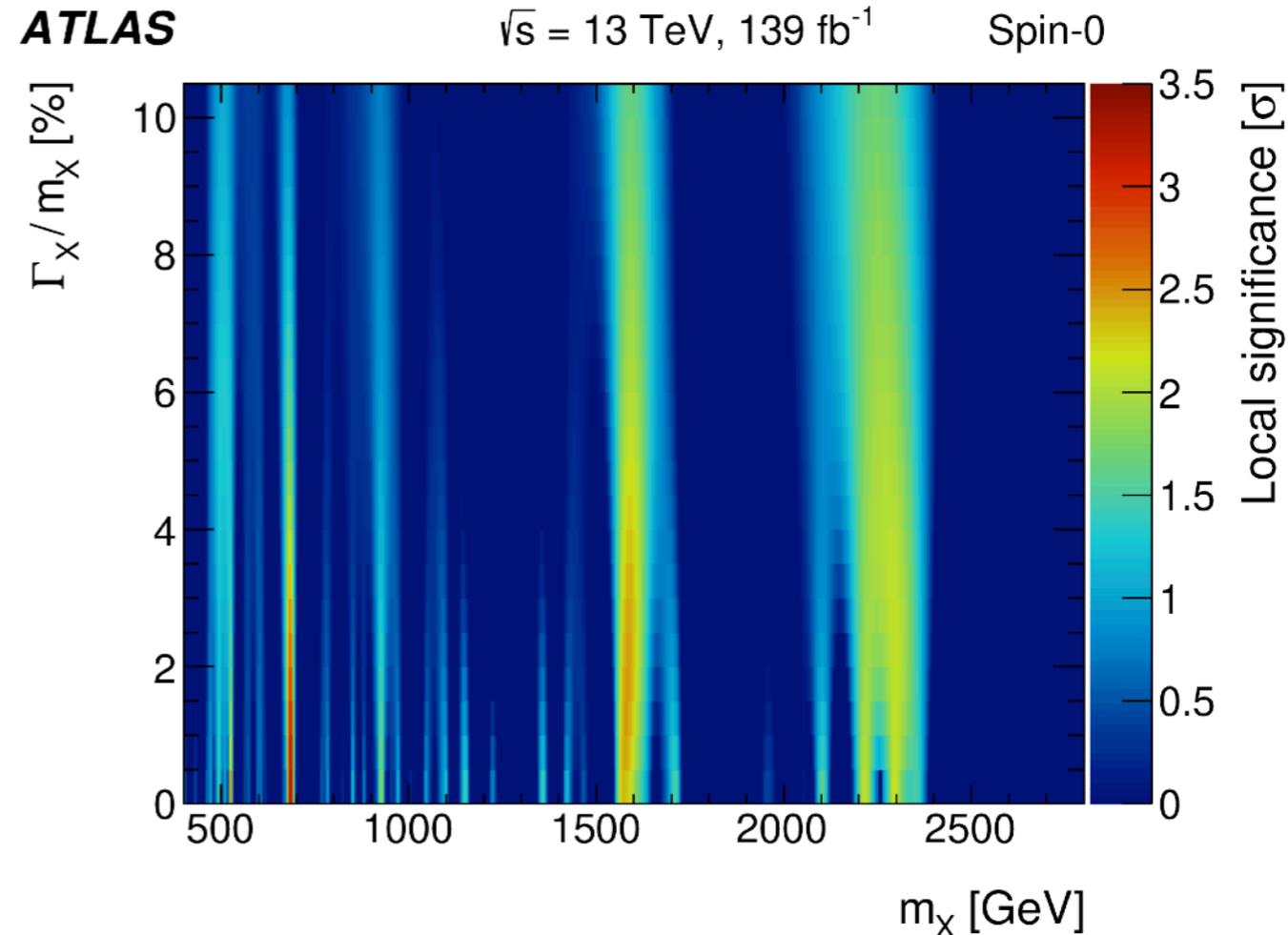
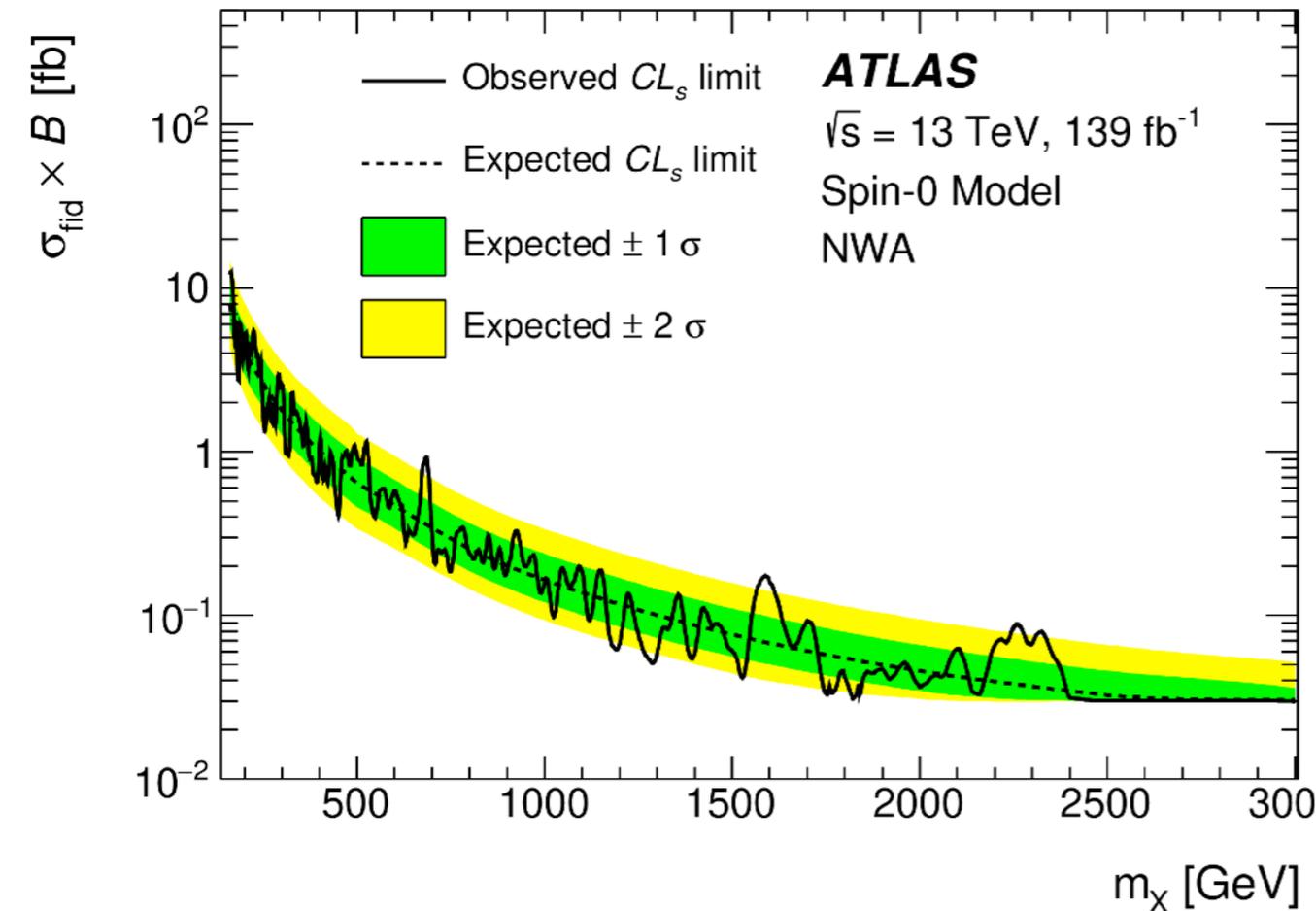
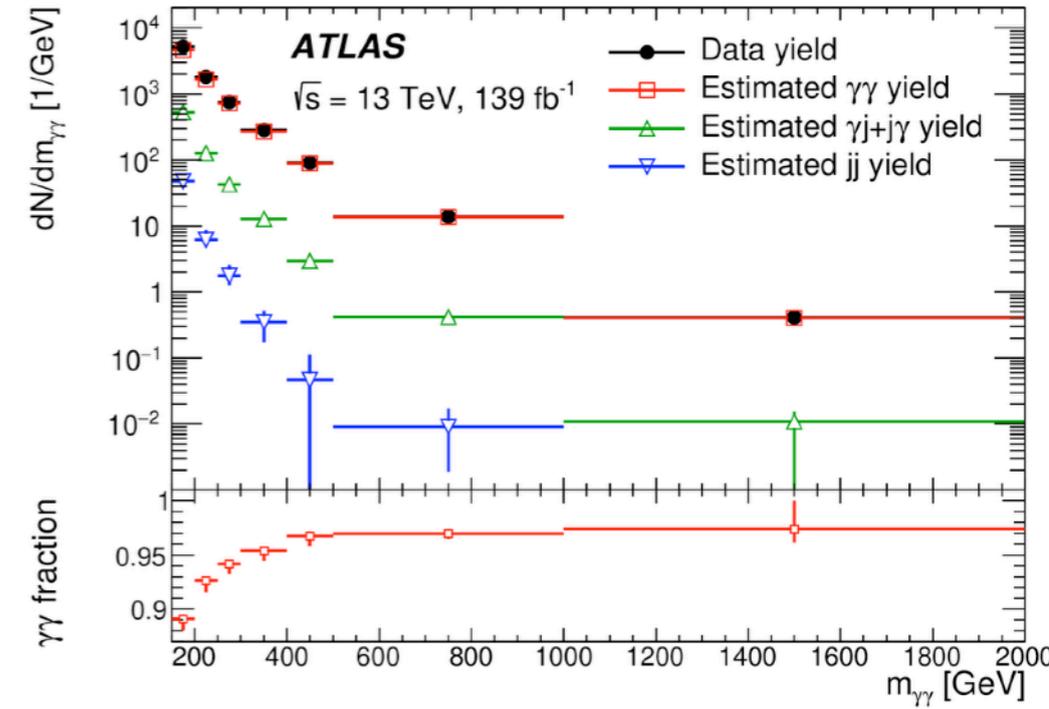
- Considering  $h(\tau\tau)h_s(bb)$  final state with  $\tau_h\tau_h, \tau_h\mu, \tau_he$  signatures of di-tau system

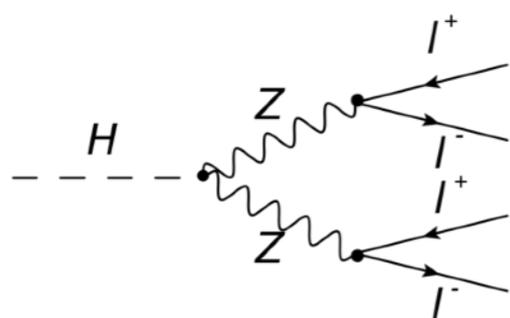




# High Mass Scalar $\rightarrow \gamma\gamma$

- Search for a resonance in di-photon mass spectrum
  - Motivated from extended Higgs sector: consider narrow ( $m > 160$  GeV) and wide ( $m > 400$  GeV) resonances
  - As well as spin-2 graviton models:  $m > 500$  GeV



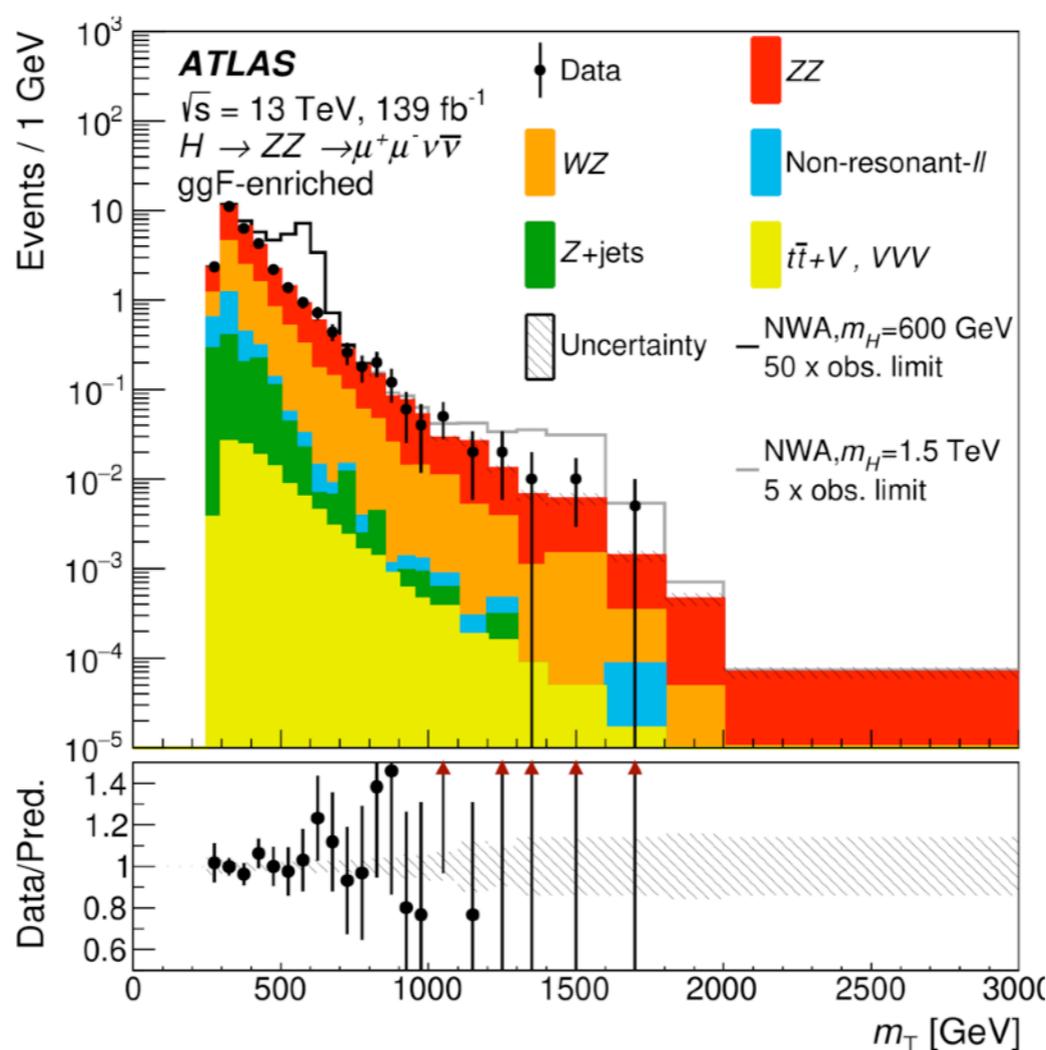
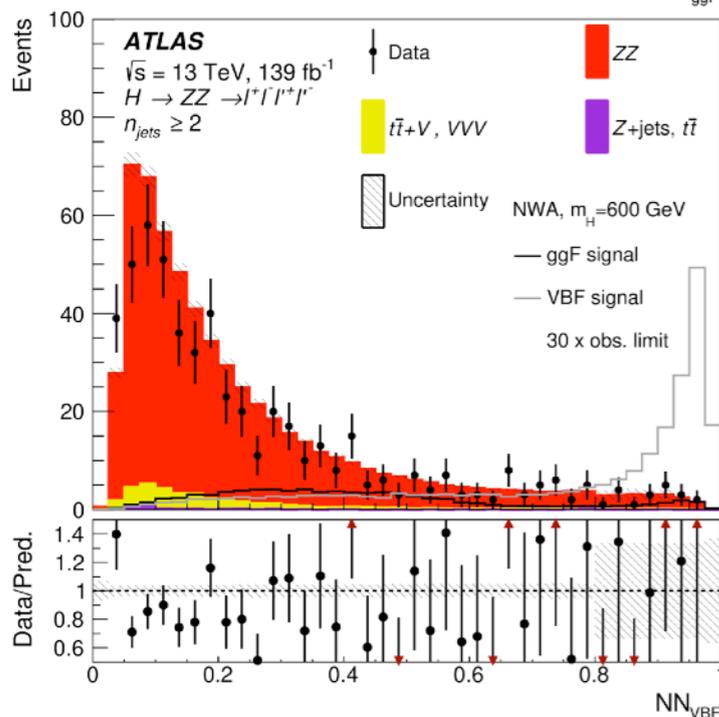
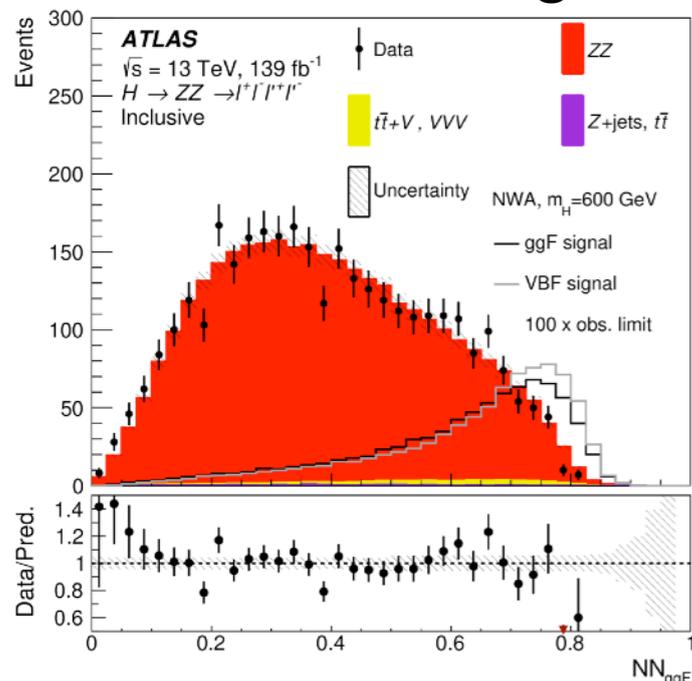


# High Mass $H \rightarrow ZZ$

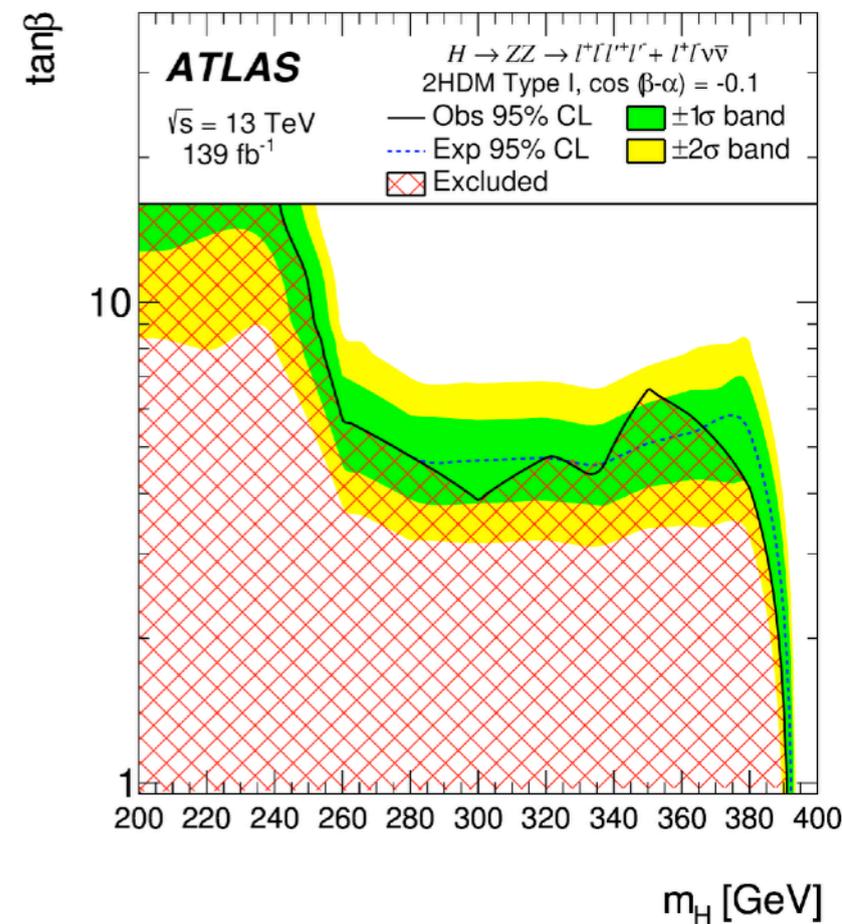
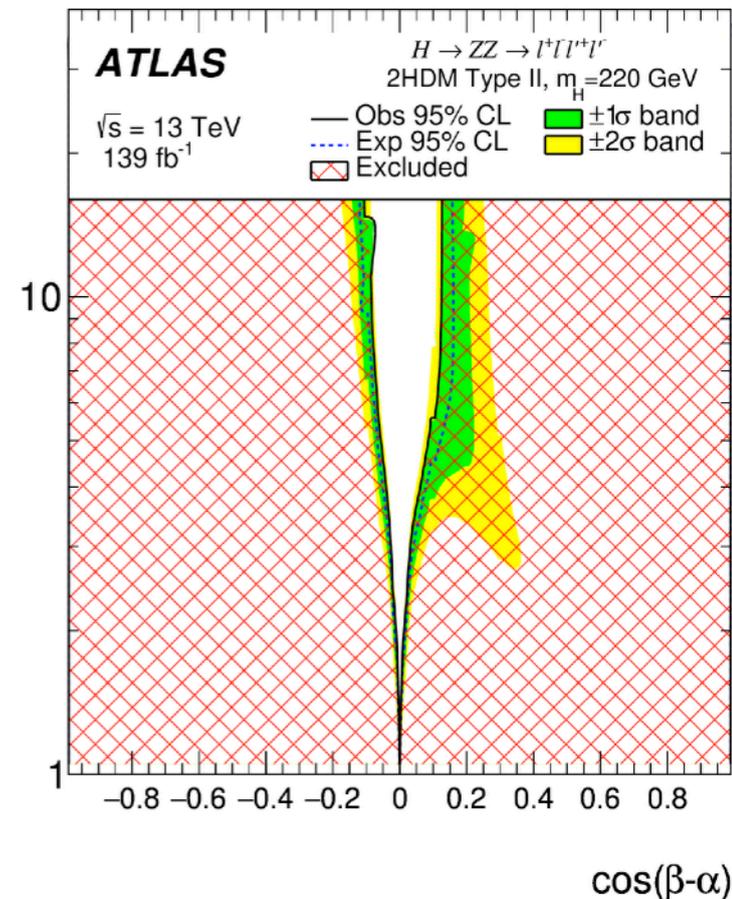
$\tan\beta$

- Consider  $llll$  and  $ll\nu\nu$  final states and ggH and VBF

- Dedicated categorization and observables  $m_{4\ell}$  and  $m_T^{\ell\nu\nu}$



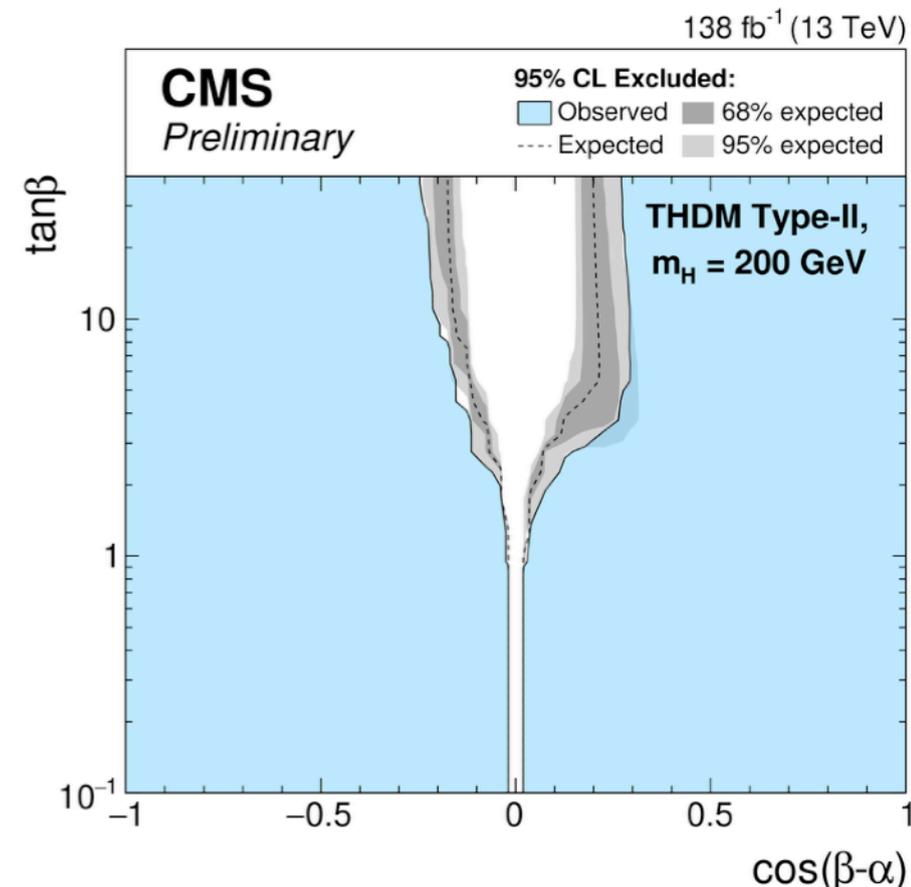
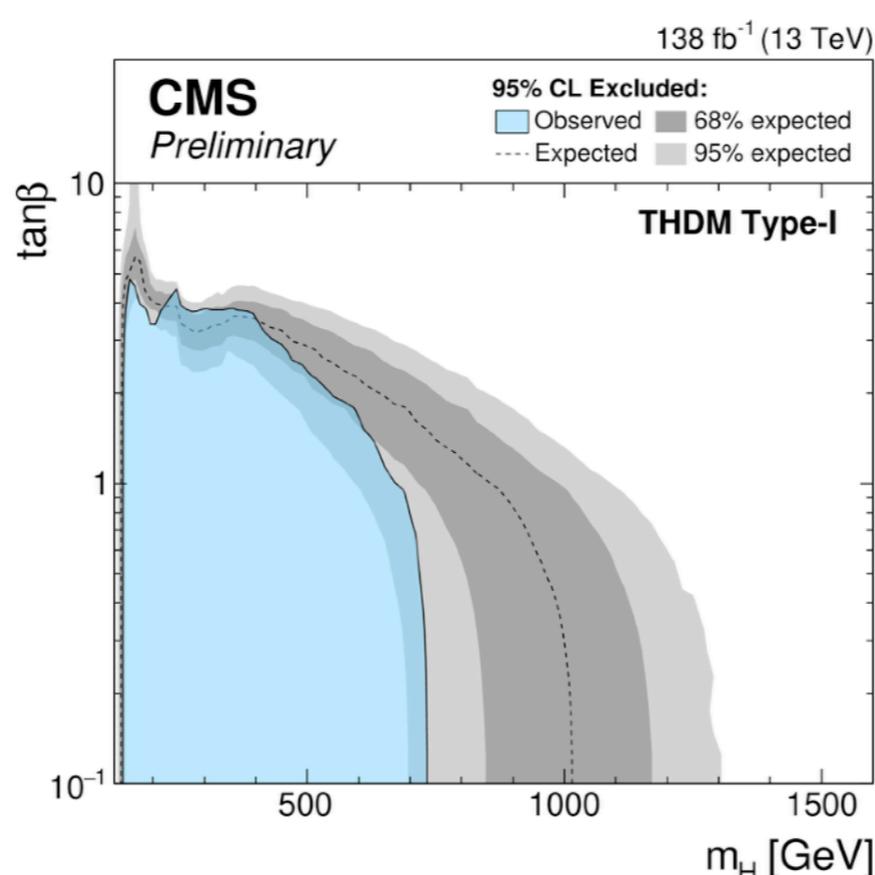
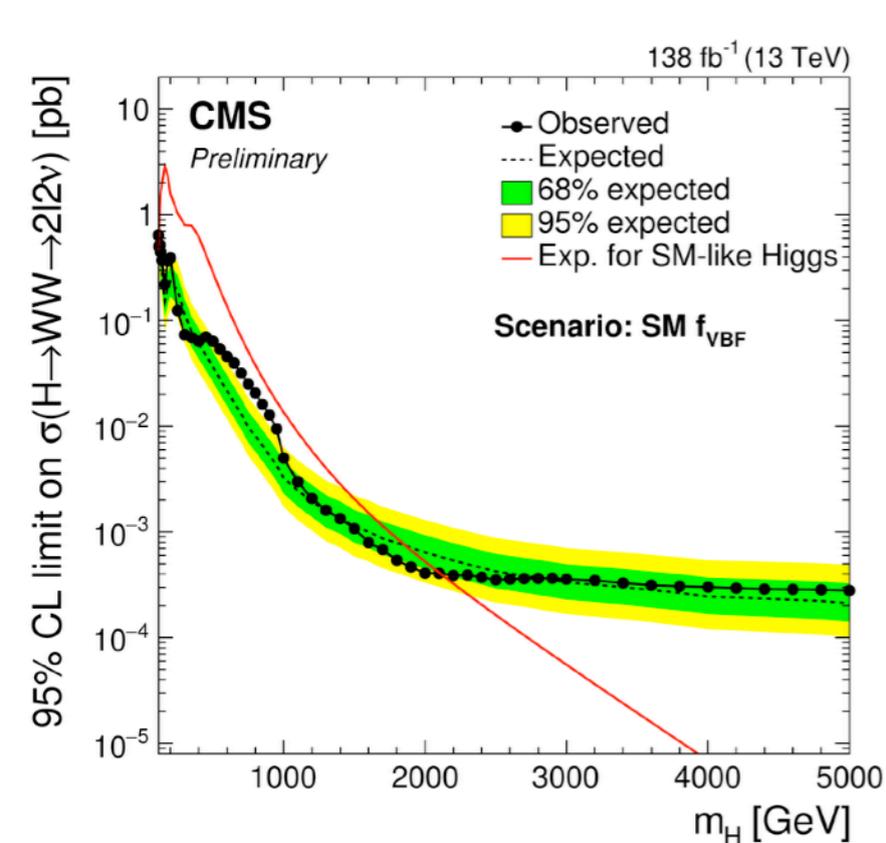
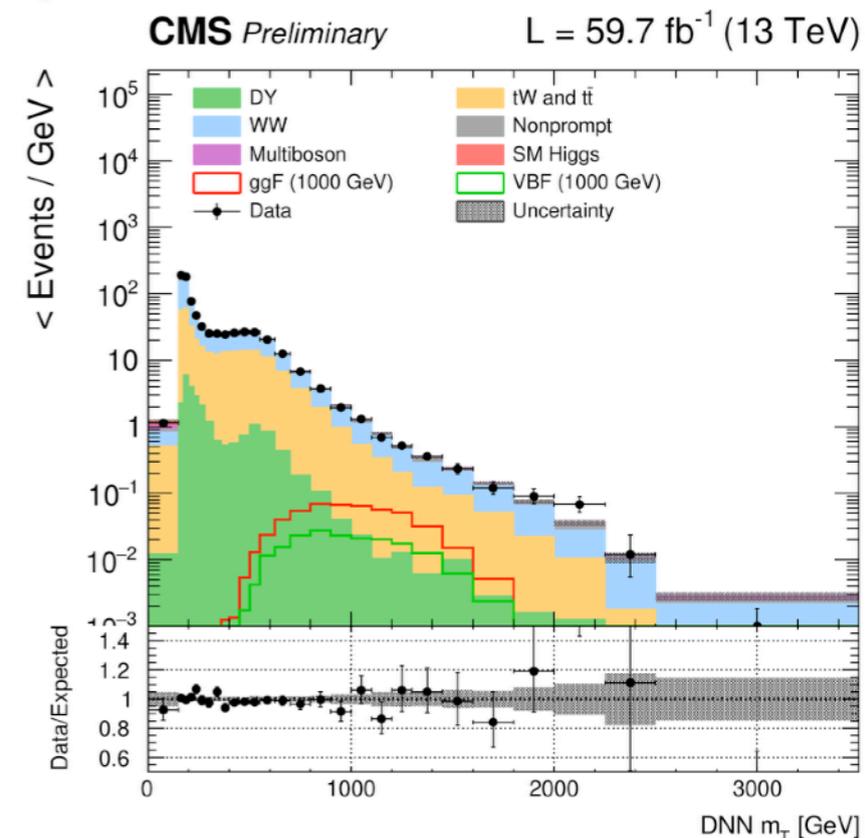
2HDM





# High Mass $H \rightarrow WW$

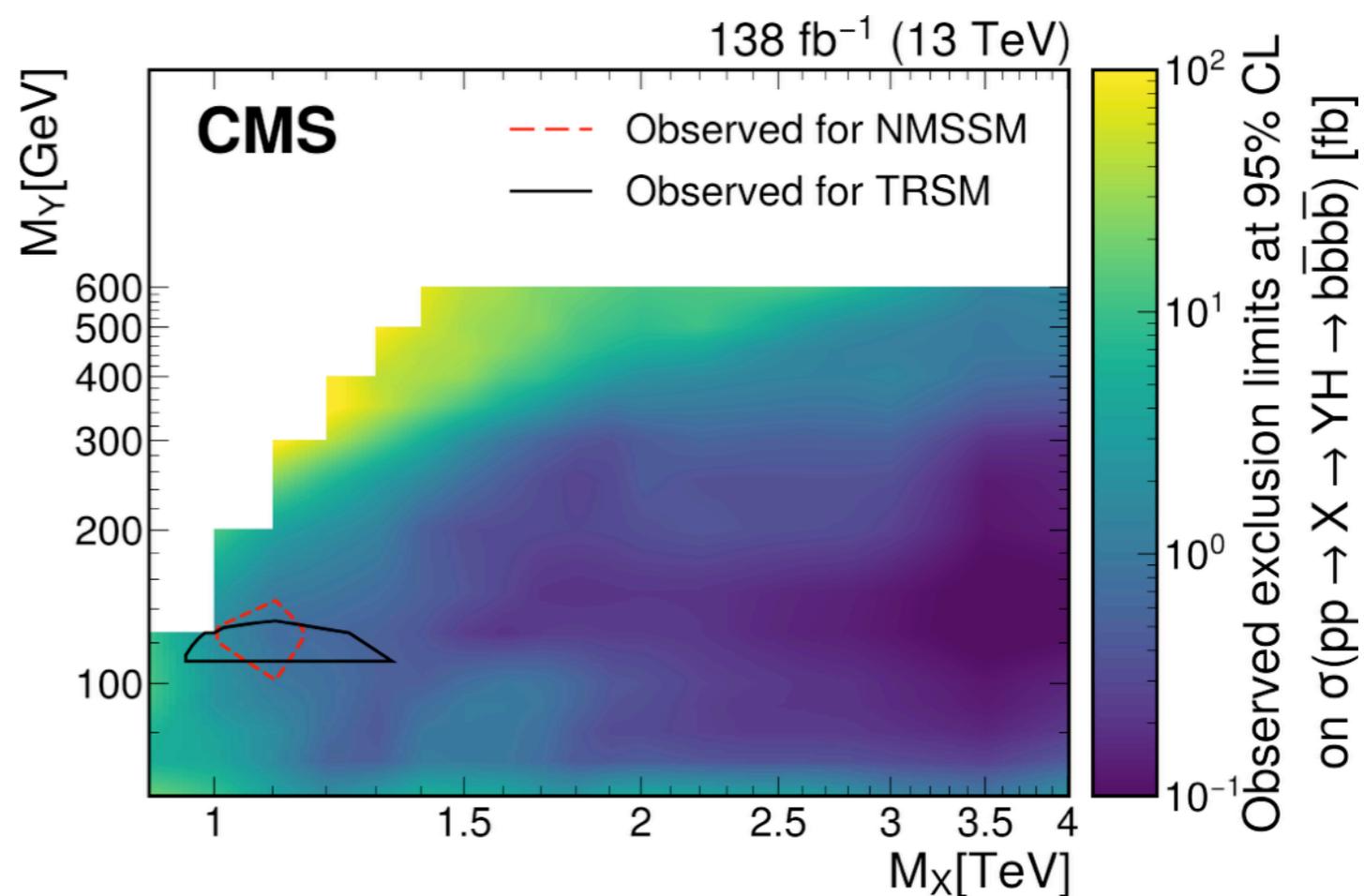
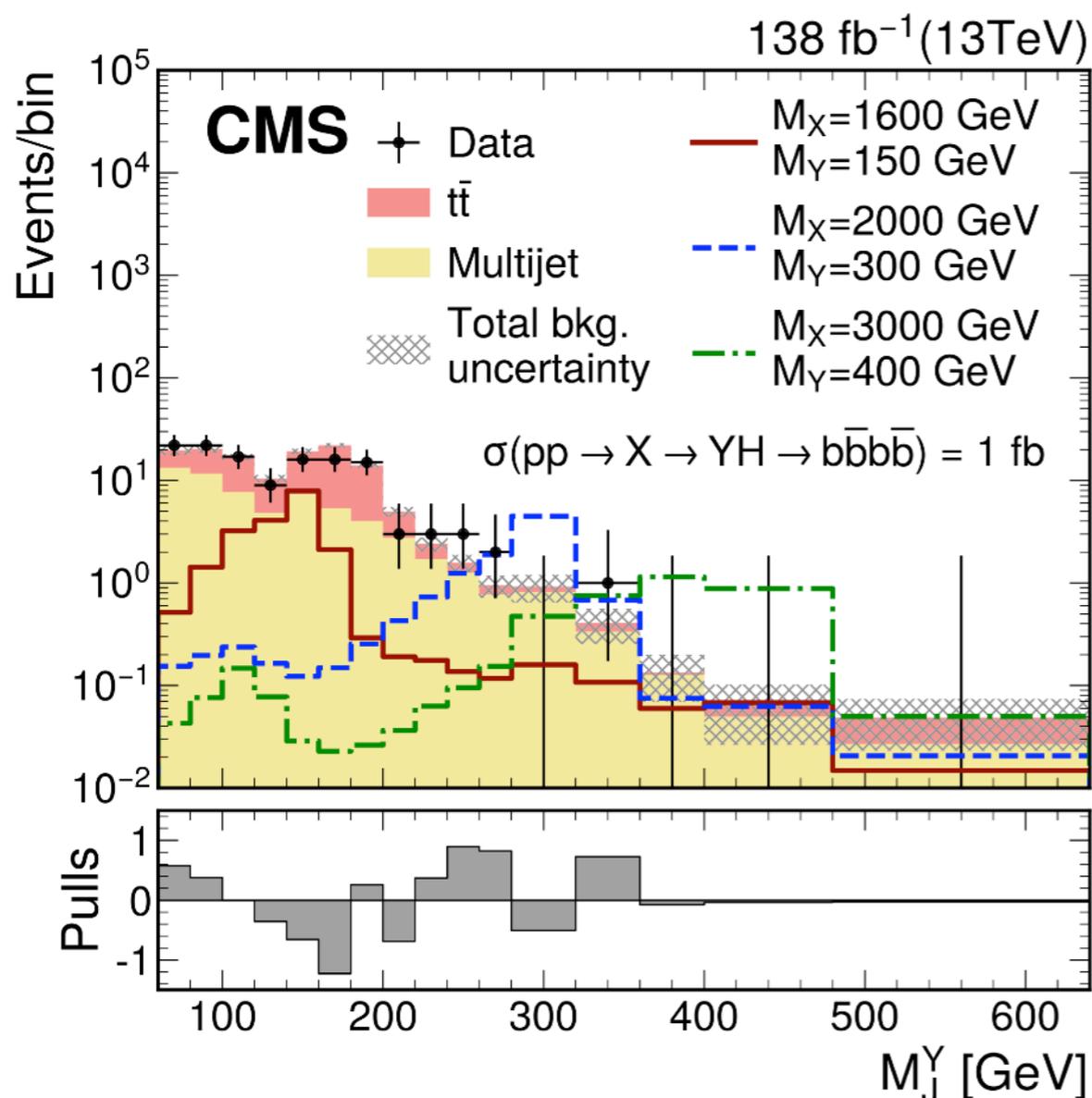
- Considering  $e\mu$ ,  $ee$ ,  $\mu\mu$  final states and  $ggH, VBF$  productions
  - Using DNN for classification between signals and bkg
  - Using  $m_T$  from DNN as final observable
- Interpretations: SM-like couplings/decays, 2HDM/MSSM
  - Consider different width scenarios; Interference with  $WW$  continuum and the SM  $H \rightarrow WW$  is taken into account

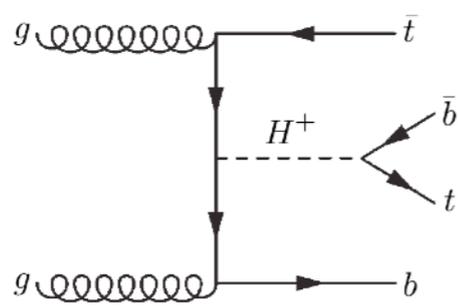




# Heavy Scalar $X \rightarrow YH$

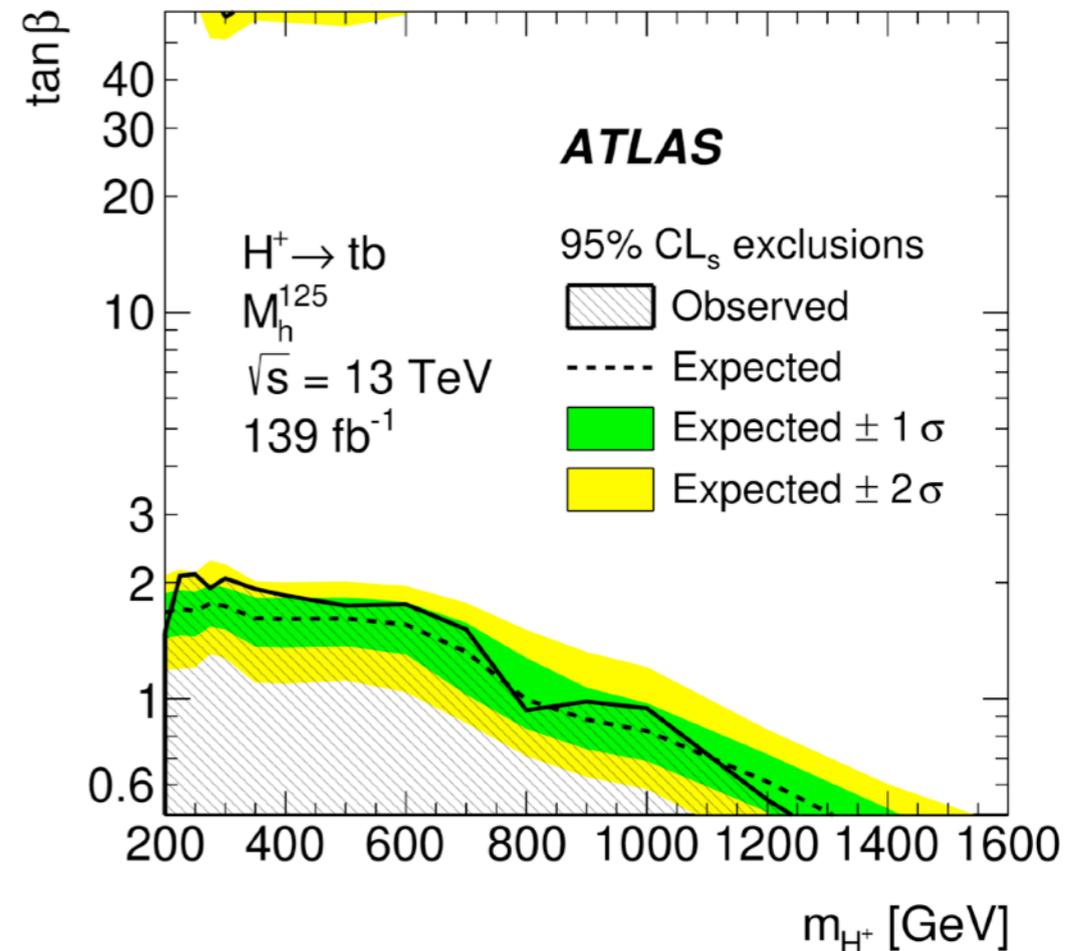
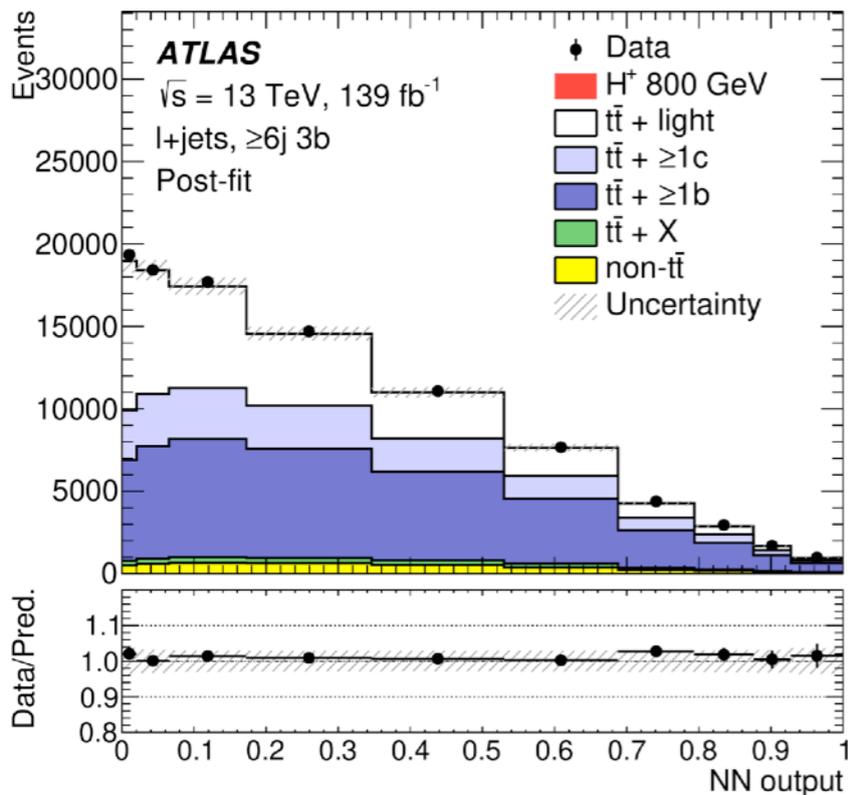
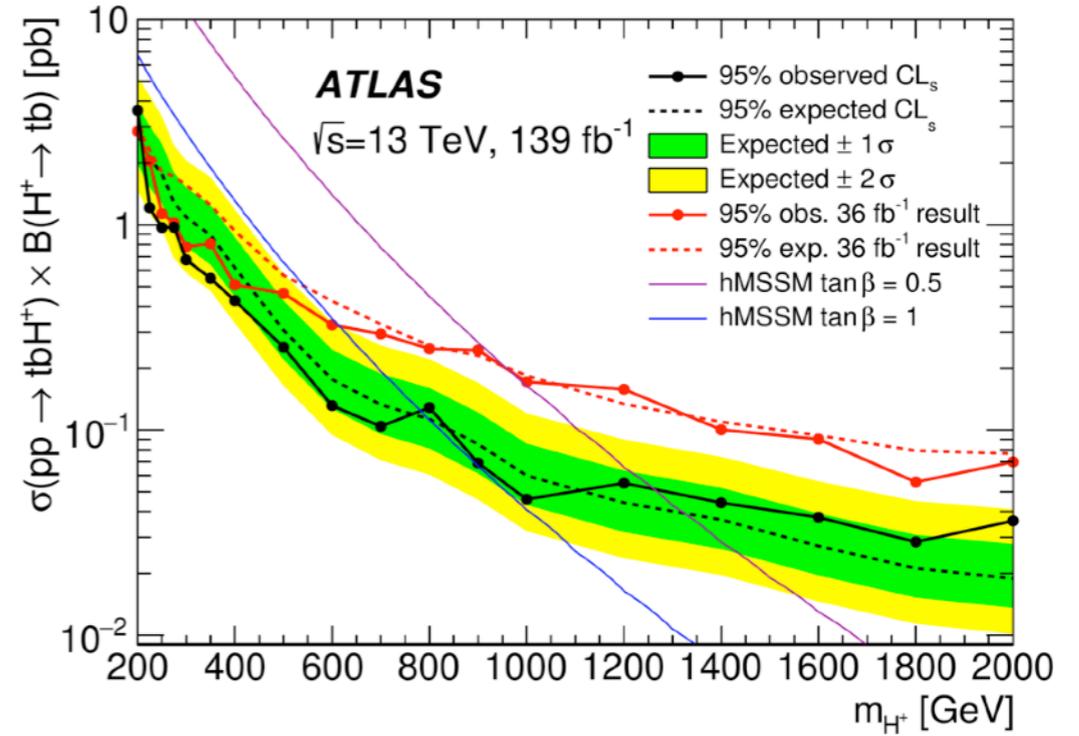
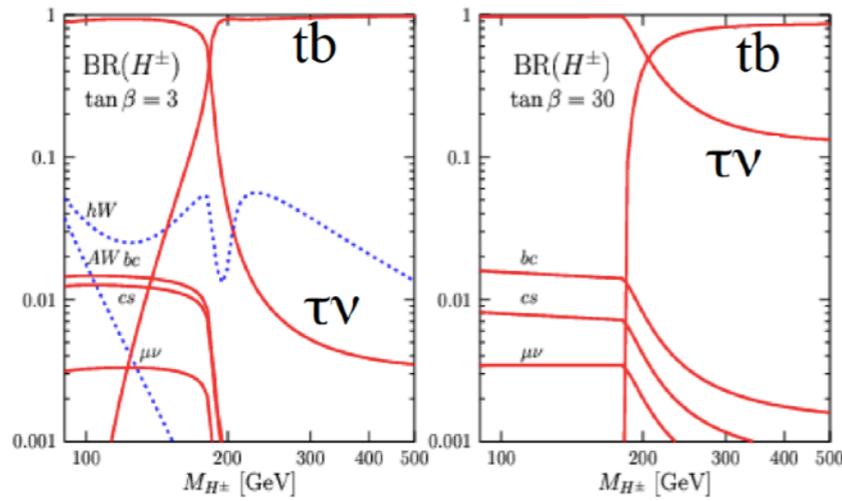
- Motivated from NMSSM, Two-Real-Scalar-Singlet extension of SM (TRSM)
- Focusing on kinematic region where
  - $m_Y < 2m_t$  — Both Y and H decay to pair of b-quarks with highest BR: 4 quarks
  - $0.9 < m_X < 4 \text{ TeV}$ ,  $60 < m_Y < 600 \text{ GeV}$  — collimated bb-pairs

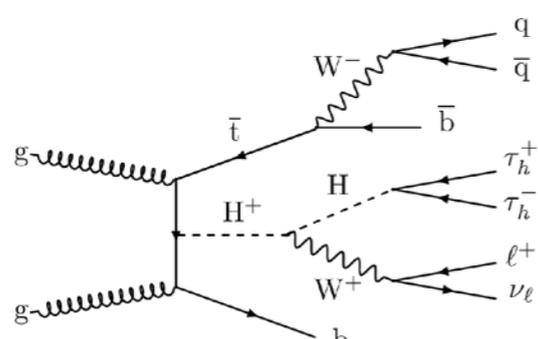




# $H^\pm \rightarrow tb$

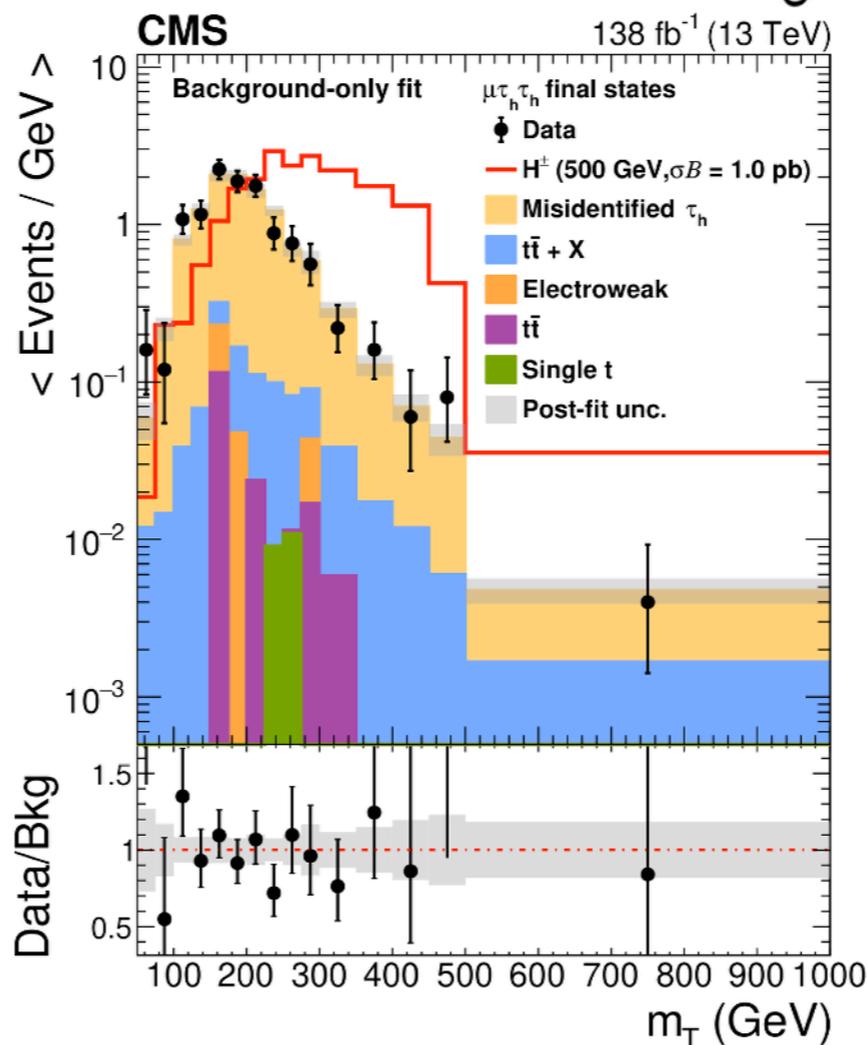
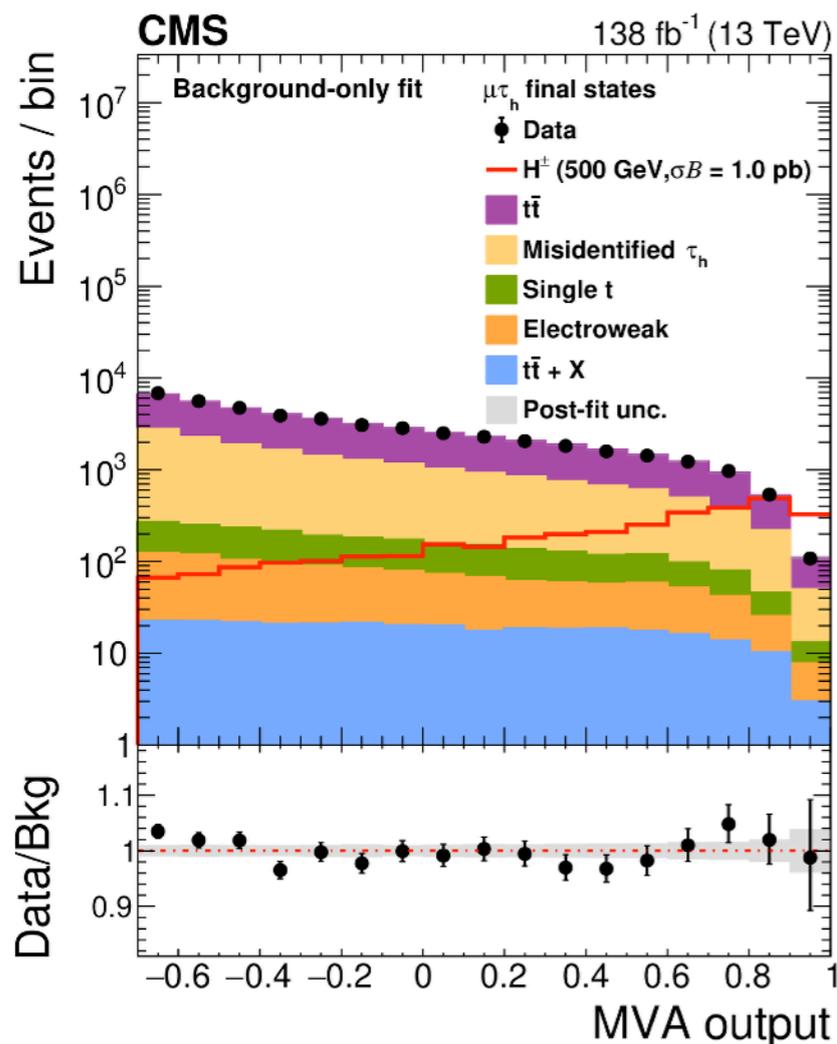
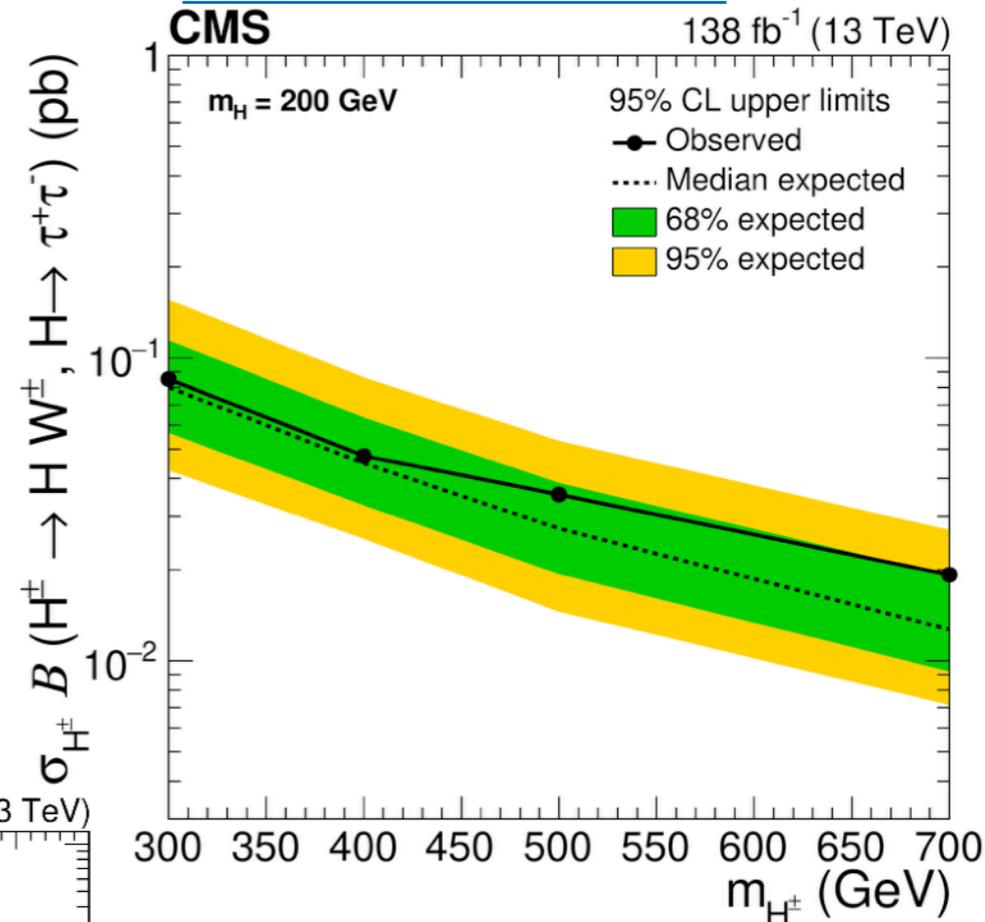
- Highest branching fraction for heavy  $H^\pm$
- Final state with single lepton and jets; Categorization based on  $N_j$  and  $N_{bj}$





$$H^\pm \rightarrow HW$$

- Focusing heavy  $H^\pm$  production  $m_{H^\pm} \gg m_t + m_b$ 
  - $m_H = 200 \text{ GeV}, m_h = 125 \text{ GeV}$
  - Considering  $\ell\tau_h+3j$  and  $\ell\tau_h\tau_h+2j$  final states using BDTG and  $m_T$  observables, rest.



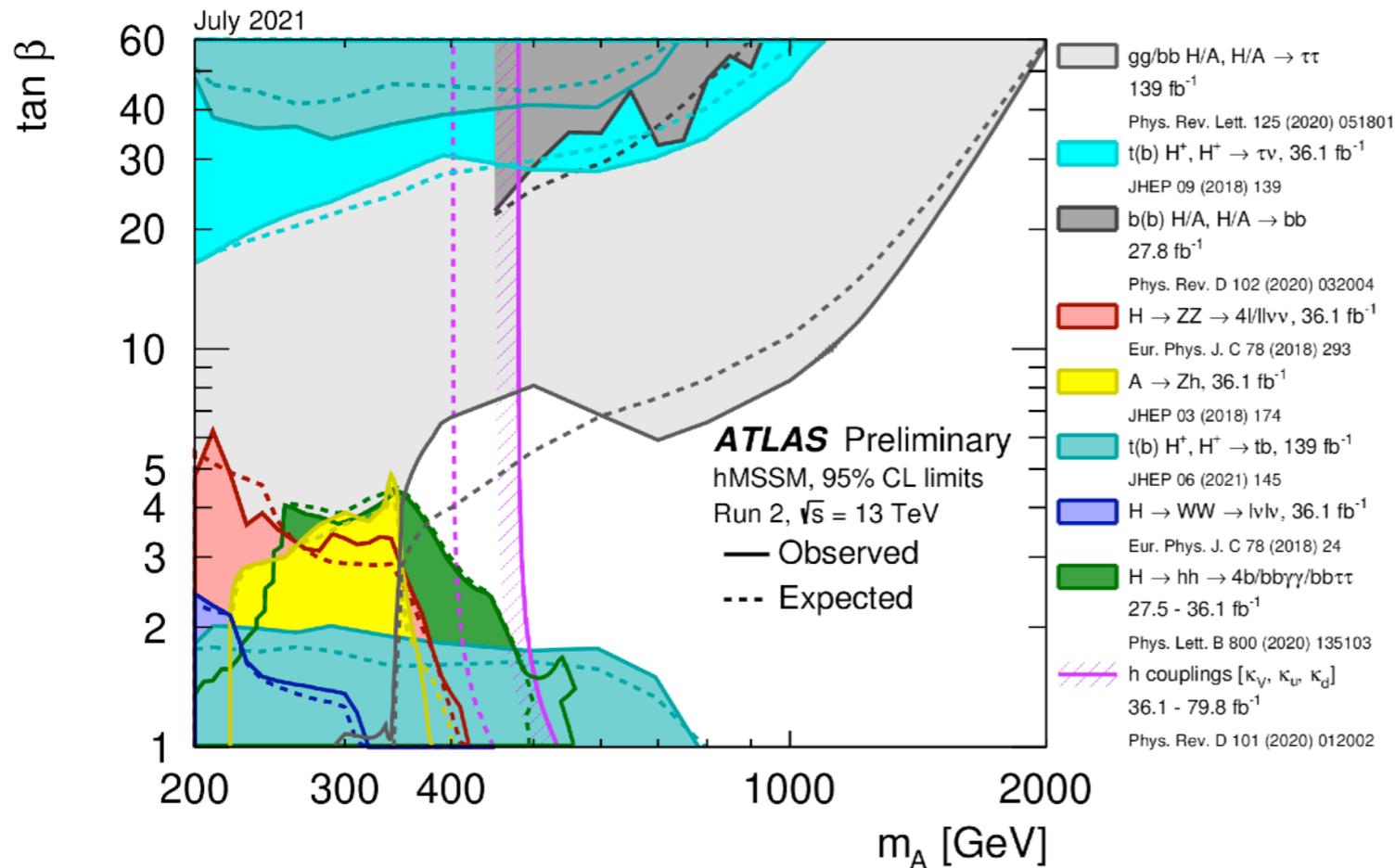
Limits:  
 0.085pb for 300 GeV  
 0.019pb for 700 GeV



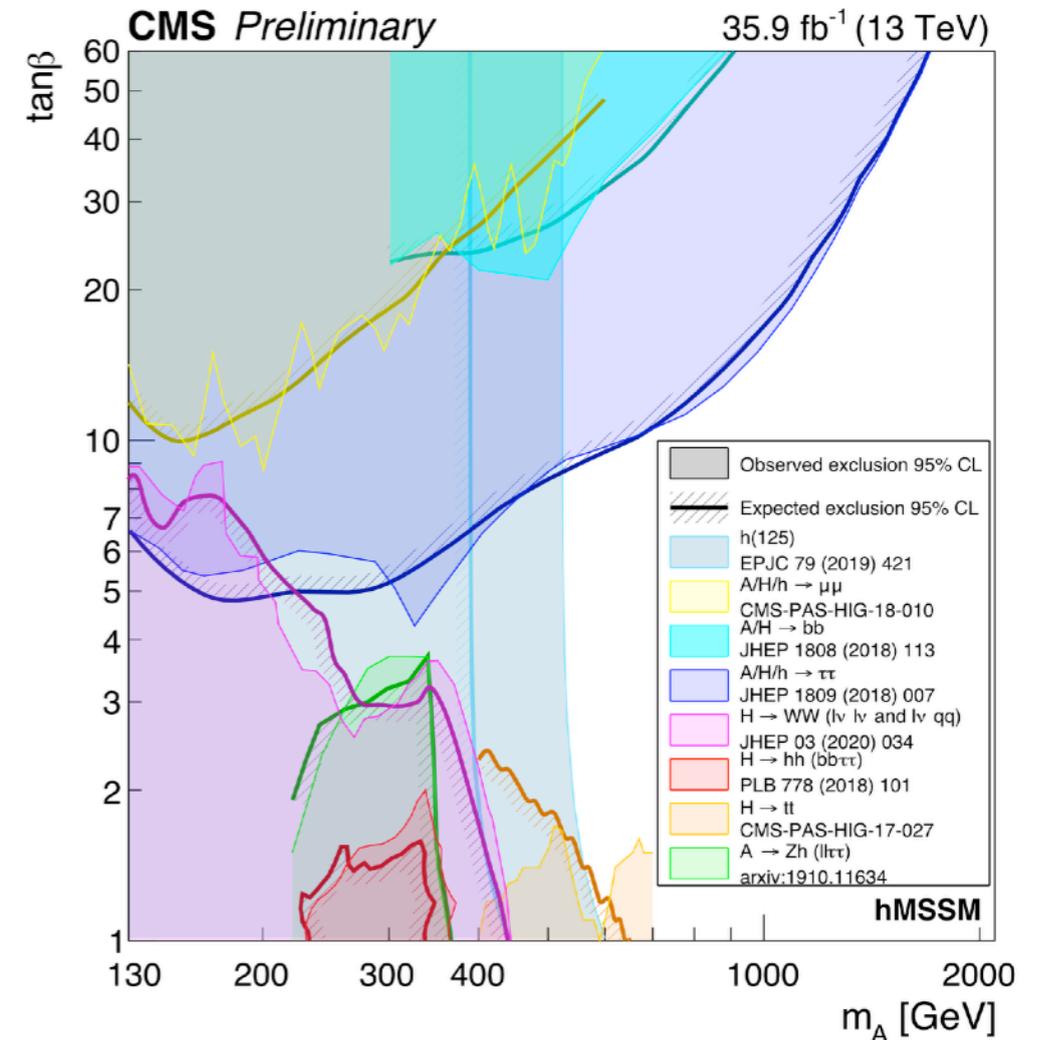
# Summary

- Very vibrant program at ATLAS and CMS to search for additional Higgs bosons
  - Light, heavy, and charged bosons
- No evidence of significant deviation from the SM background prediction
  - Improved analyses techniques and object identification let to broadening phase space for the searches
- Many of the Run 2 analyses are still ongoing. Stay tuned!

## ATLAS Results



## CMS Results



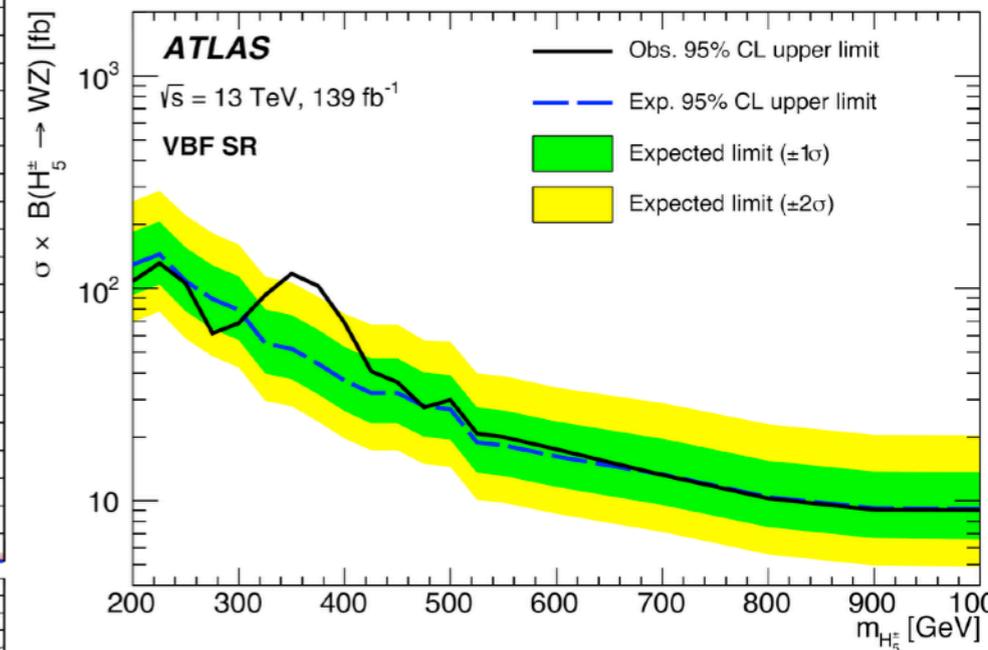
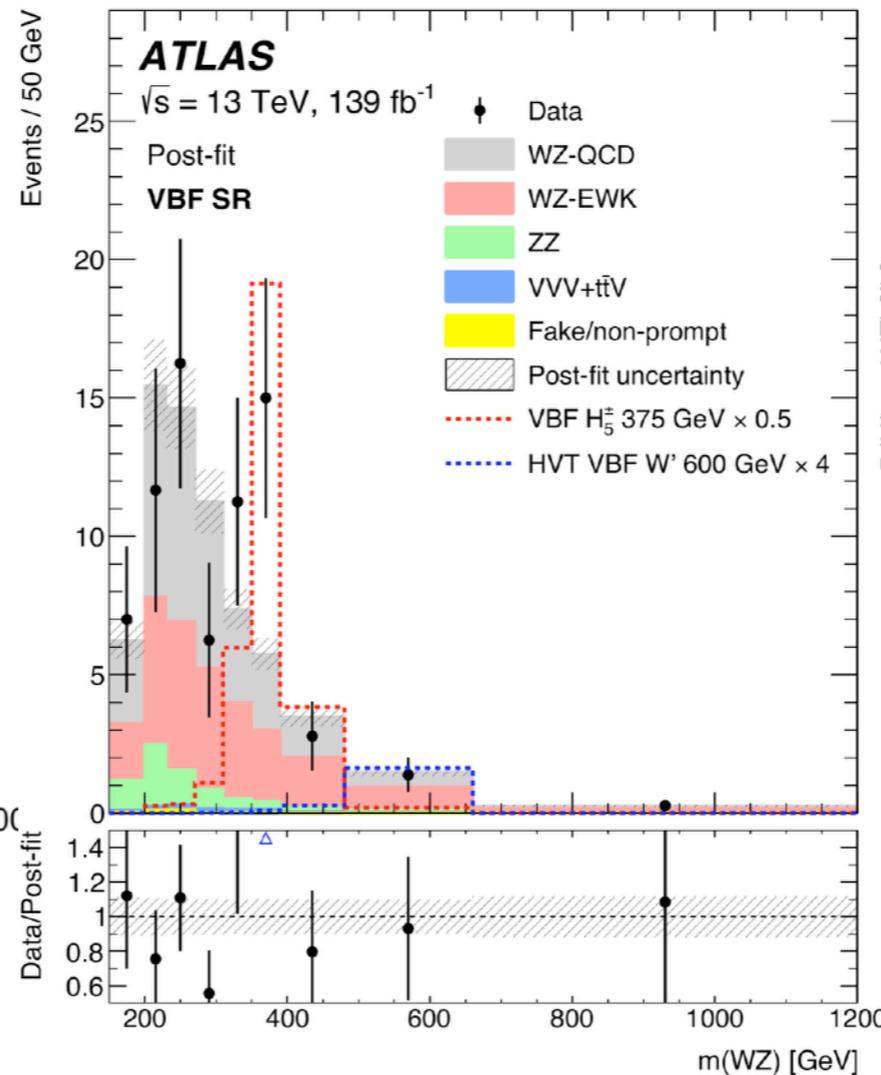
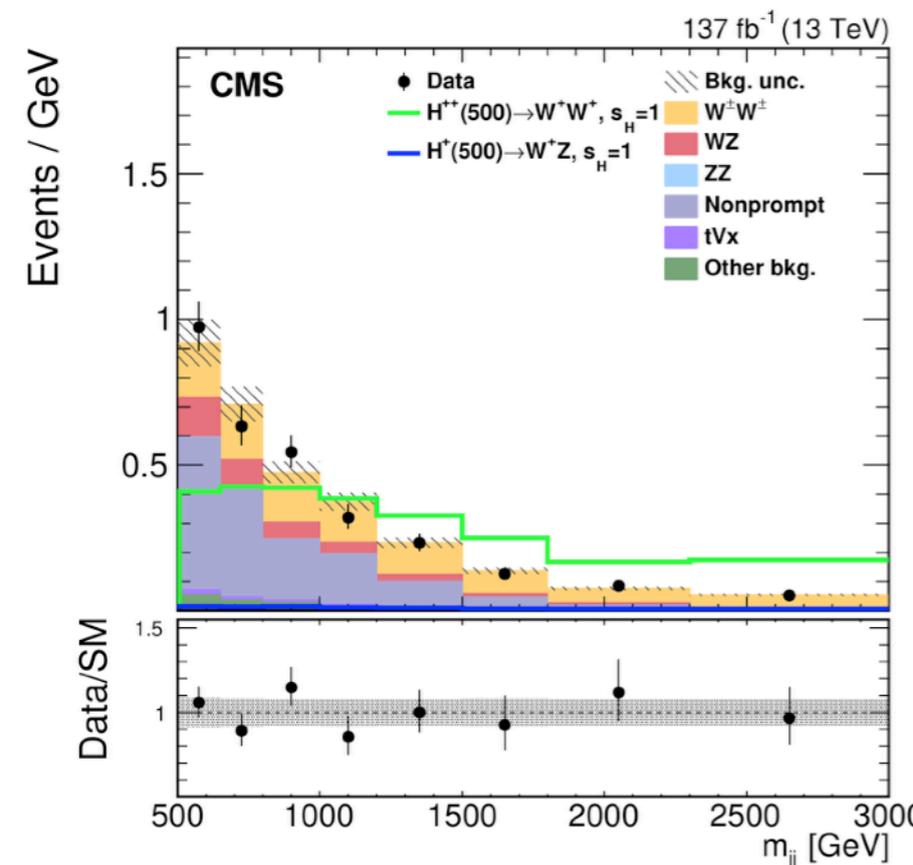
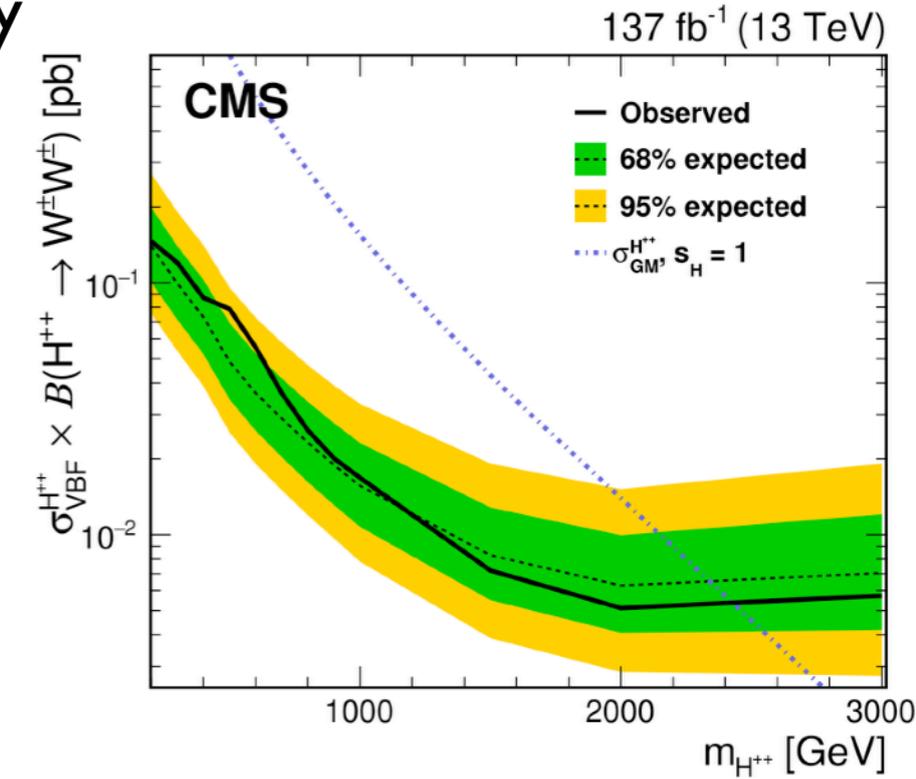
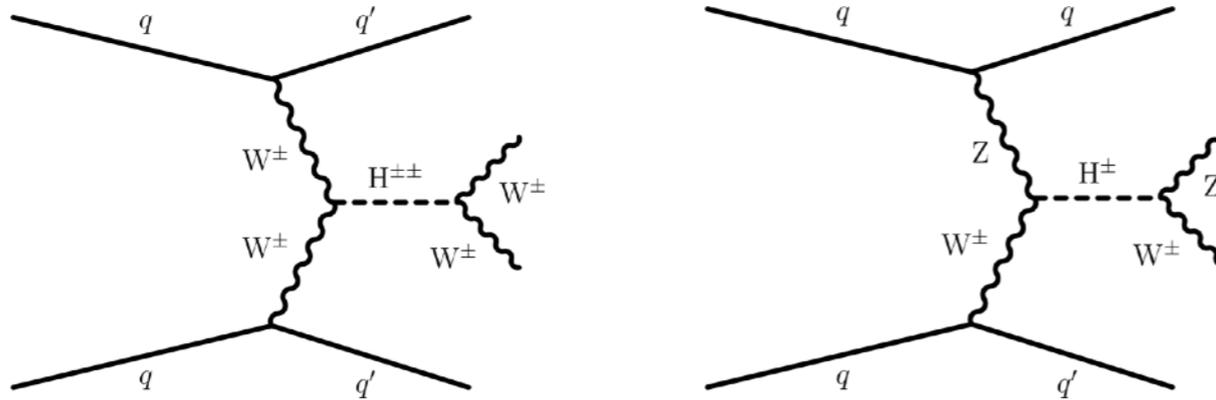


# BACKUP



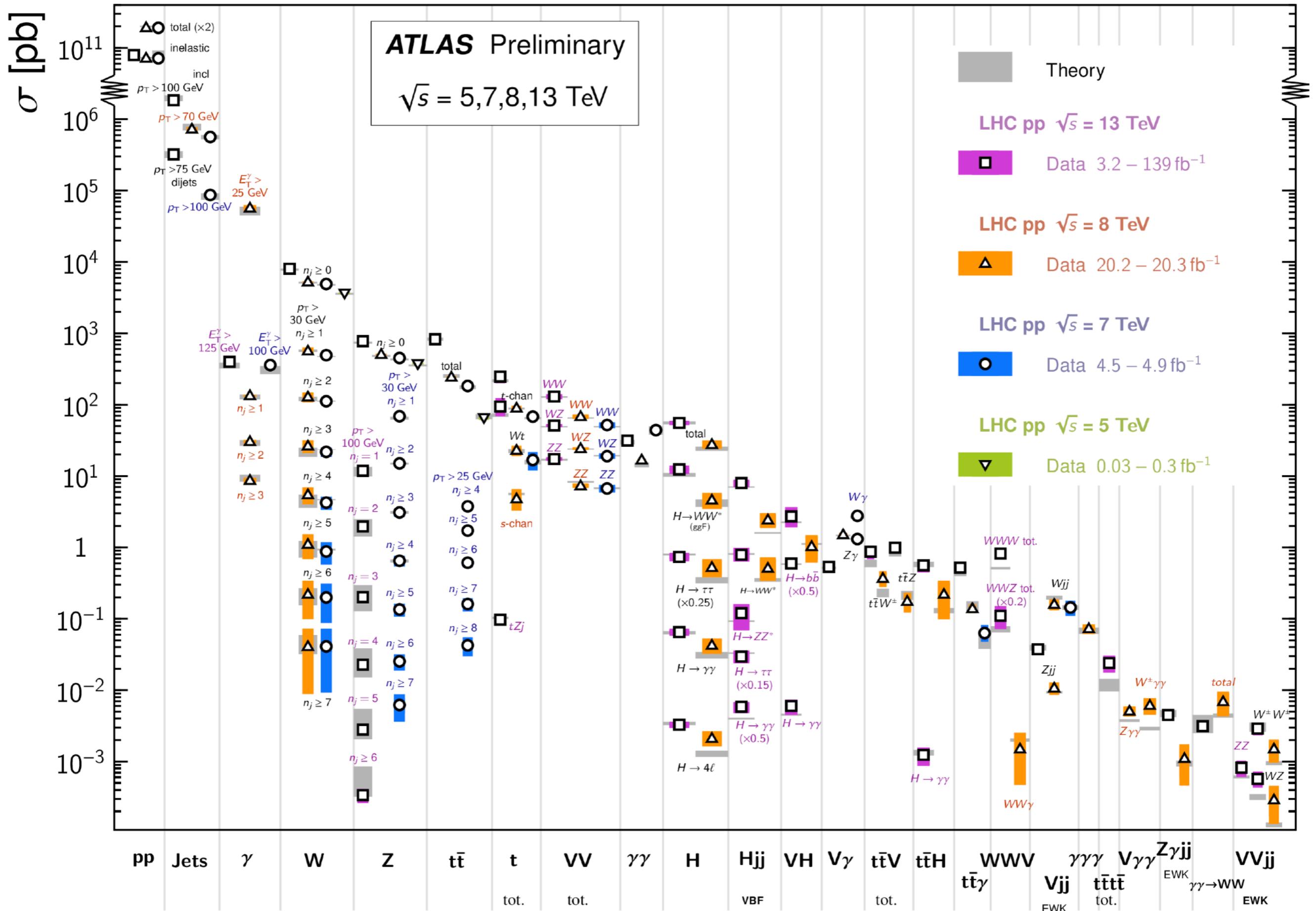
# VBF $H^{\pm}/\pm\pm \rightarrow WZ/WW$

- Considering leptonic final state with di-jet VBF topology



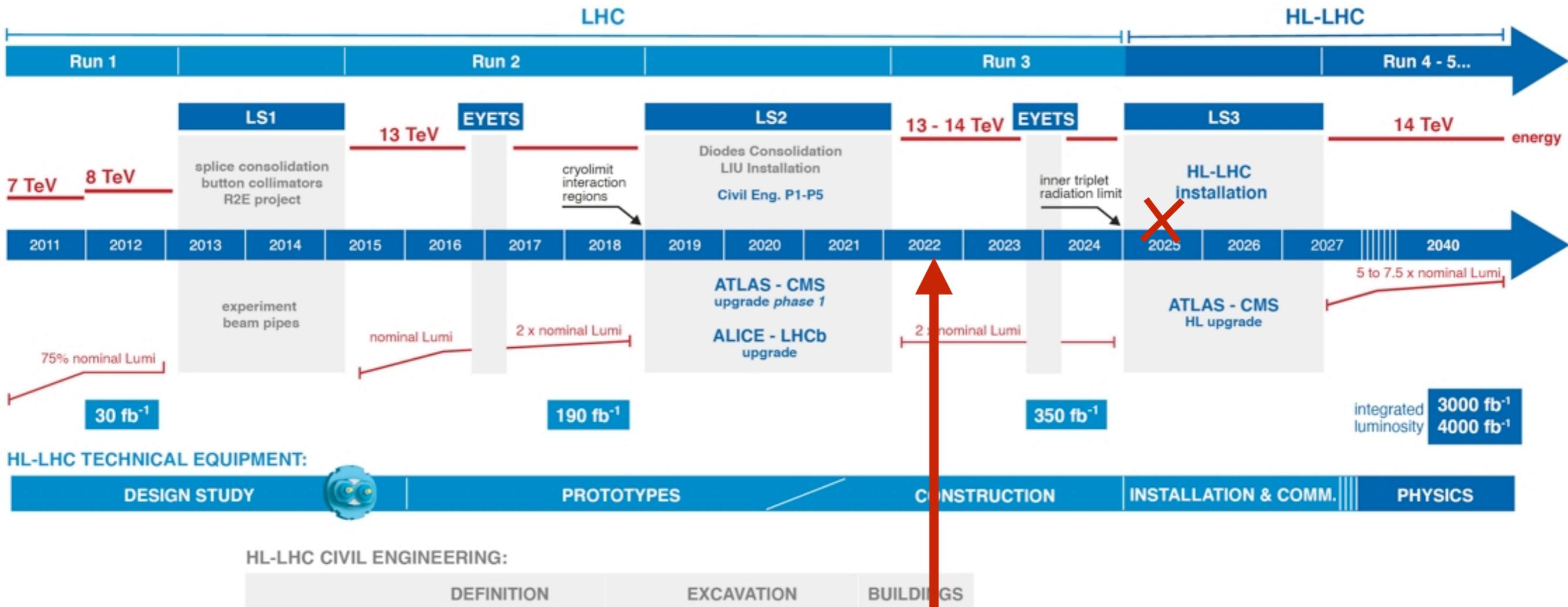
# Standard Model Production Cross Section Measurements

Status: February 2022





# LHC / HL-LHC Plan



We are here!  
 Twice more time to go!  
 Twenty times more data to come!  
 And before all those, Run 3 has 'just' started!

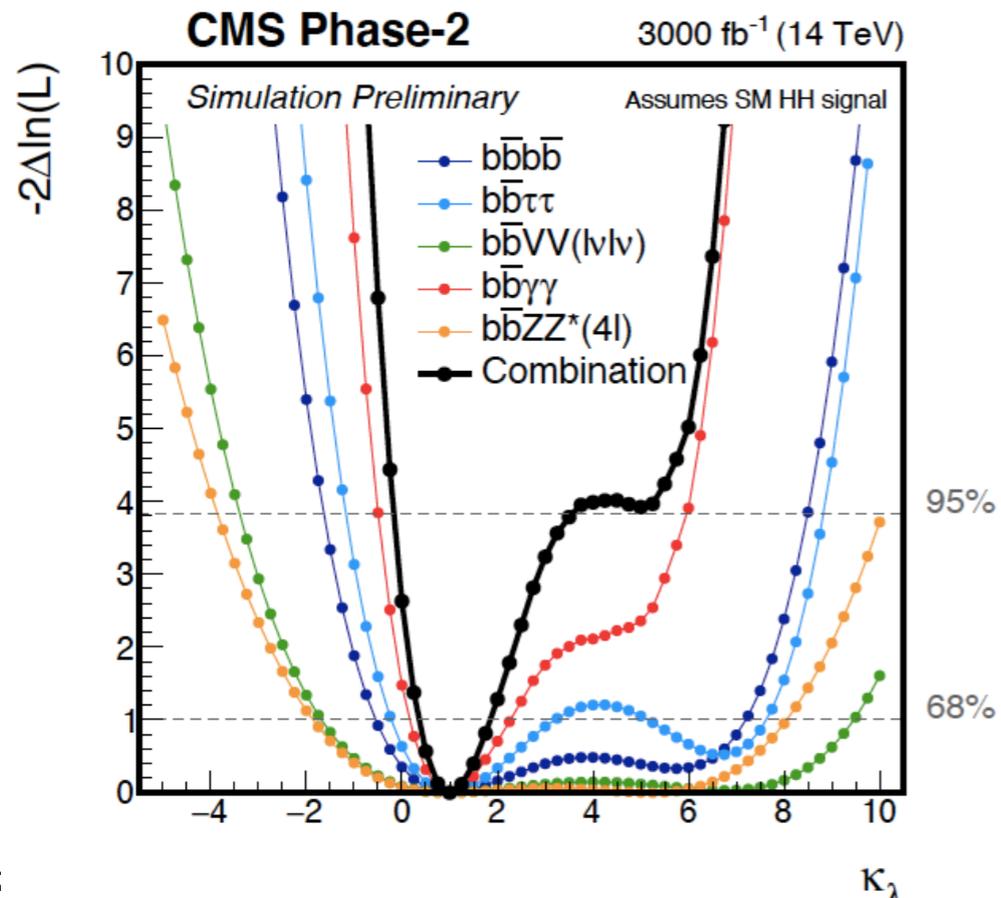
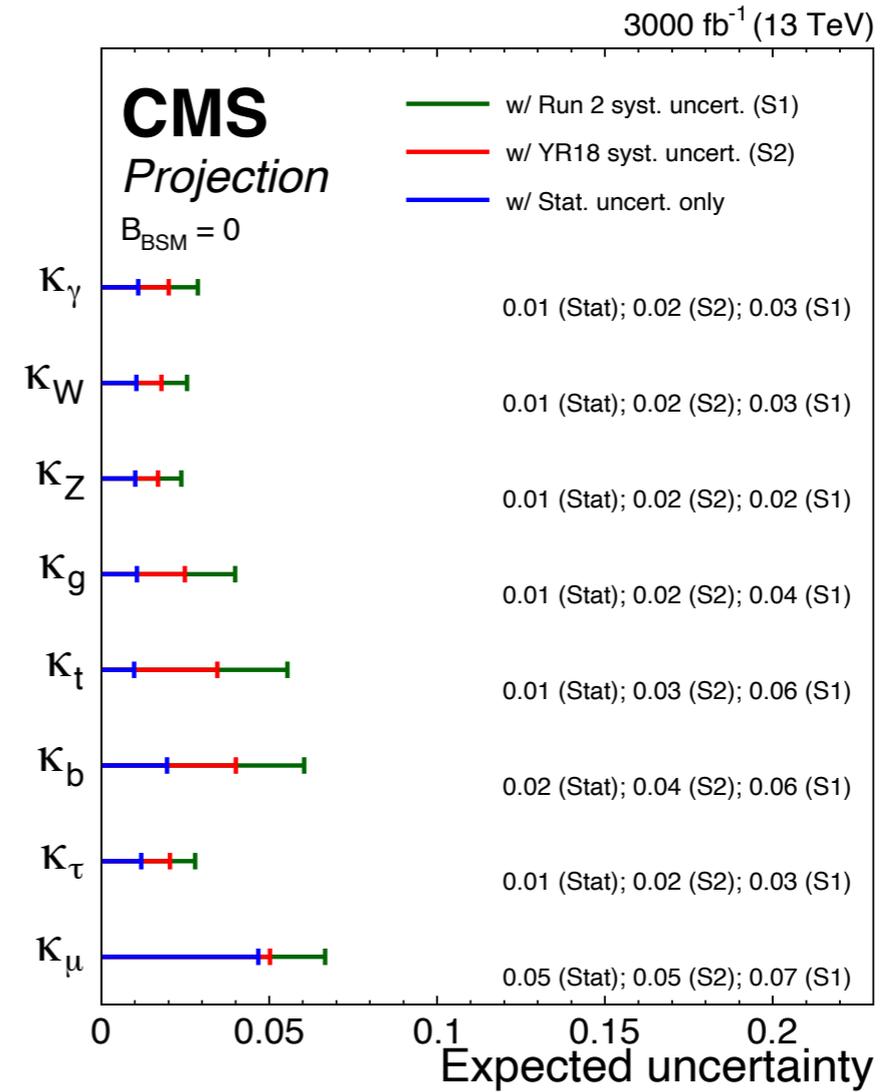
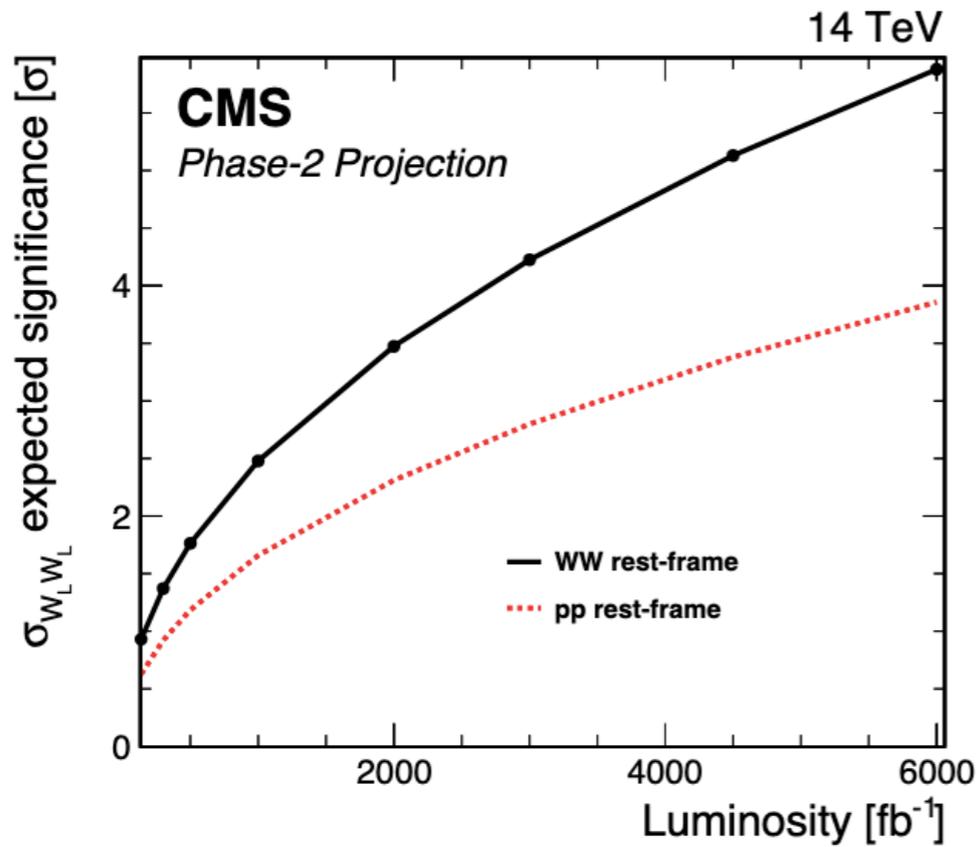


# Looking Into the Future

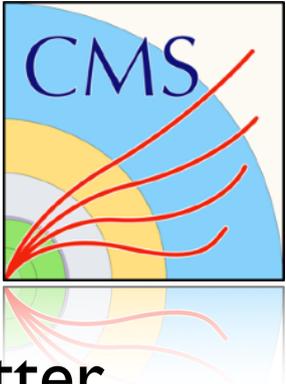
[CMS-FTR-18-011](#)

[CMS-FTR-18-019](#)

[CMS-FTR-21-001](#)



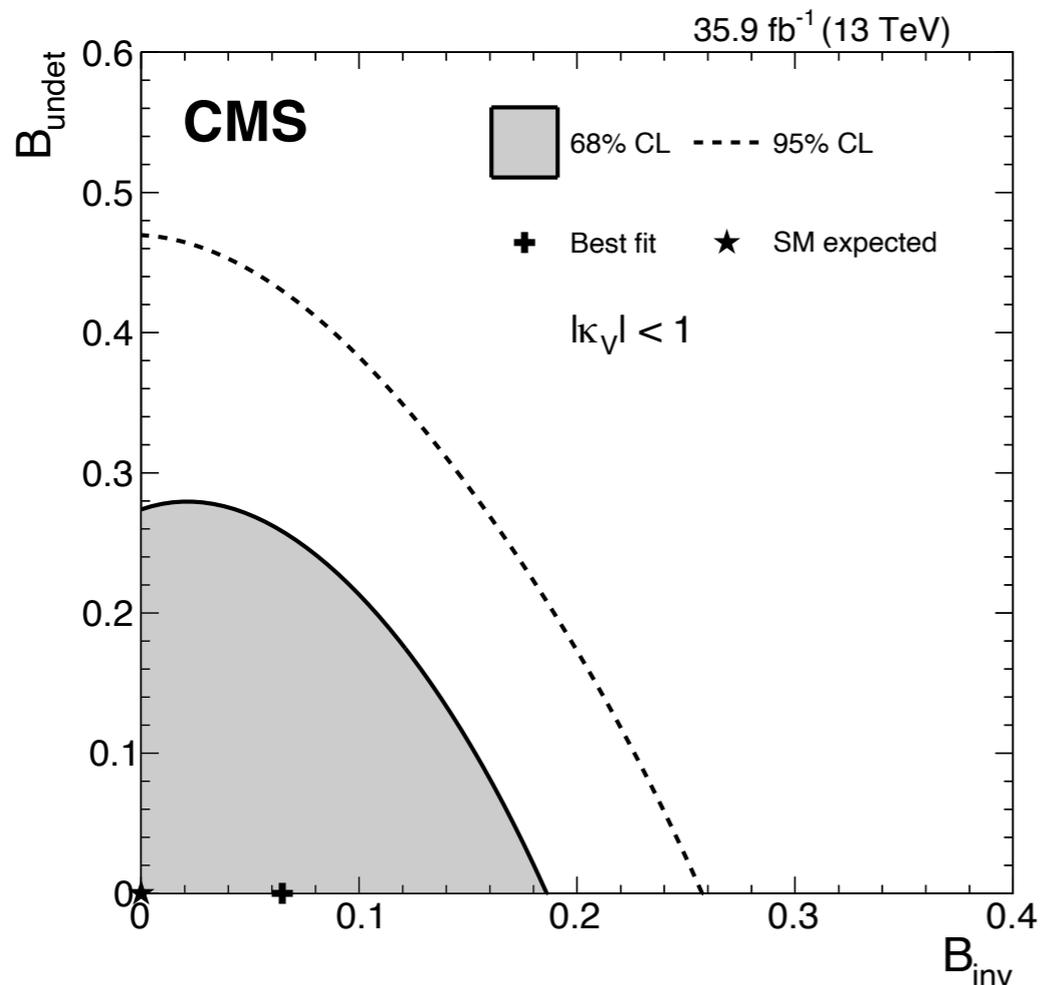
Channel	Significance		95% CL limit on $\sigma_{\text{HH}}/\sigma_{\text{HH}}^{\text{SM}}$	
	Stat. + syst.	Stat. only	Stat. + syst.	Stat. only
$b\bar{b}b\bar{b}$	0.95	1.2	2.1	1.6
$b\bar{b}\tau\tau$	1.4	1.6	1.4	1.3
$b\bar{b}WW(l\nu l\nu)$	0.56	0.59	3.5	3.3
$b\bar{b}\gamma\gamma$	1.8	1.8	1.1	1.1
$b\bar{b}ZZ(llll)$	0.37	0.37	6.6	6.5
Combination	2.6	2.8	0.77	0.71



# Can there be non-SM decay?

- The SM does not explain our current observations of the universe (dark matter, naturalness, matter-antimatter asymmetry, etc..)
- The Higgs is the unique particle of its kind — this could be one of the keys to beyond the SM physics

$B_{\text{BSM}} \approx 35\% \text{ @ } 95\% \text{ CL}$   
 Eur. Phys. J. C 79 (2019) 421



Composite Higgs with LFV decays  
 NMSSM

2HDM + S models  $H \rightarrow aa$

Type II,  $\tan \beta = 0.5$

[arXiv:1312.4992](https://arxiv.org/abs/1312.4992)

