



УНИВЕРЗИТЕТ У БЕОГРАДУ
ИНСТИТУТ ЗА ФИЗИКУ | БЕОГРАД
ИНСТИТУТ ОД НАЦИОНАЛНОГ
ЗНАЧАЈА ЗА РЕПУБЛИКУ СРБИЈУ

Extended Higgs Sector Subgroup - Experimental Updates

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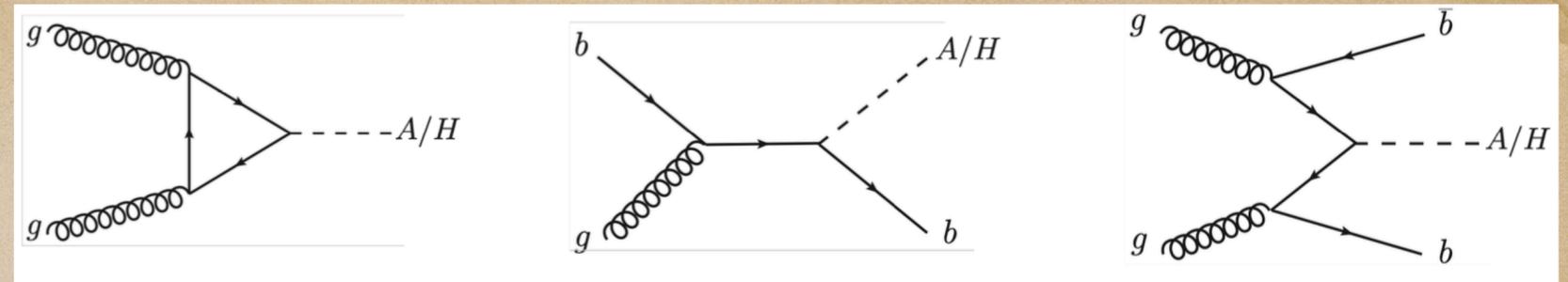
Overview

- ◆ Summary of experimental results
 - ◆ Interpretation and combination
 - ◆ Output formats and information - marked on slides
 - ◆ FD - final discriminant, Lim - limit (1D, 2D, table) HEPdata - FD, Lim
- ◆ I will not discuss it today, but many improvements in experimental techniques allow us to probe new phase space
 - ◆ Large-R jets, flavour tagging which now includes dedicated charm-tagging, new developments for the trigger, multivariate techniques

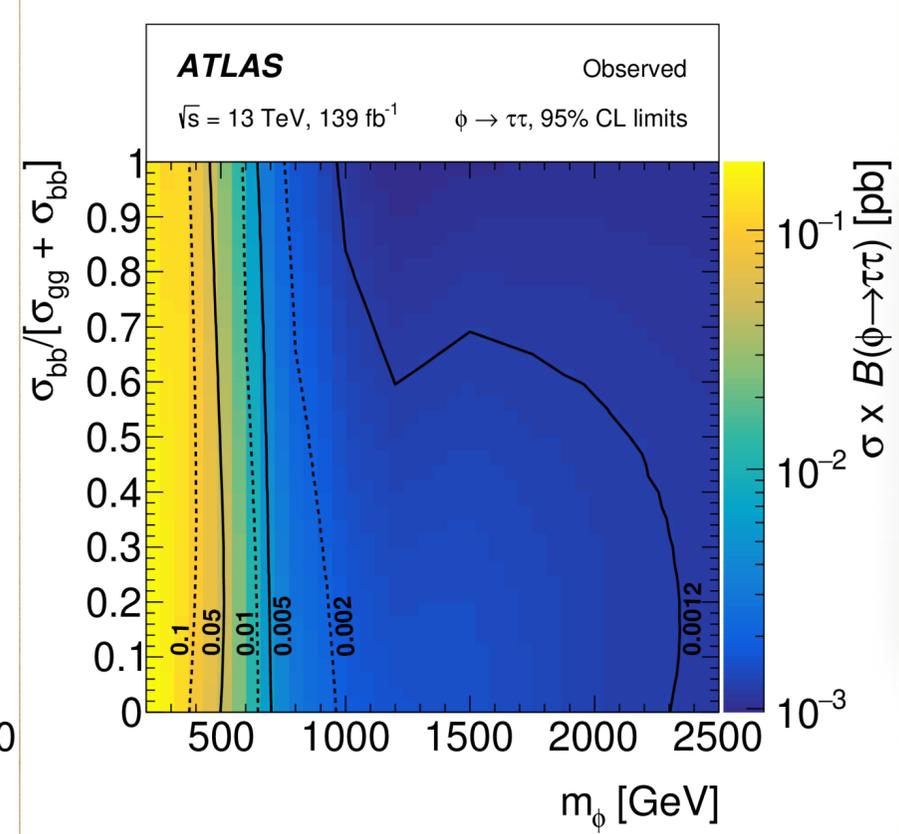
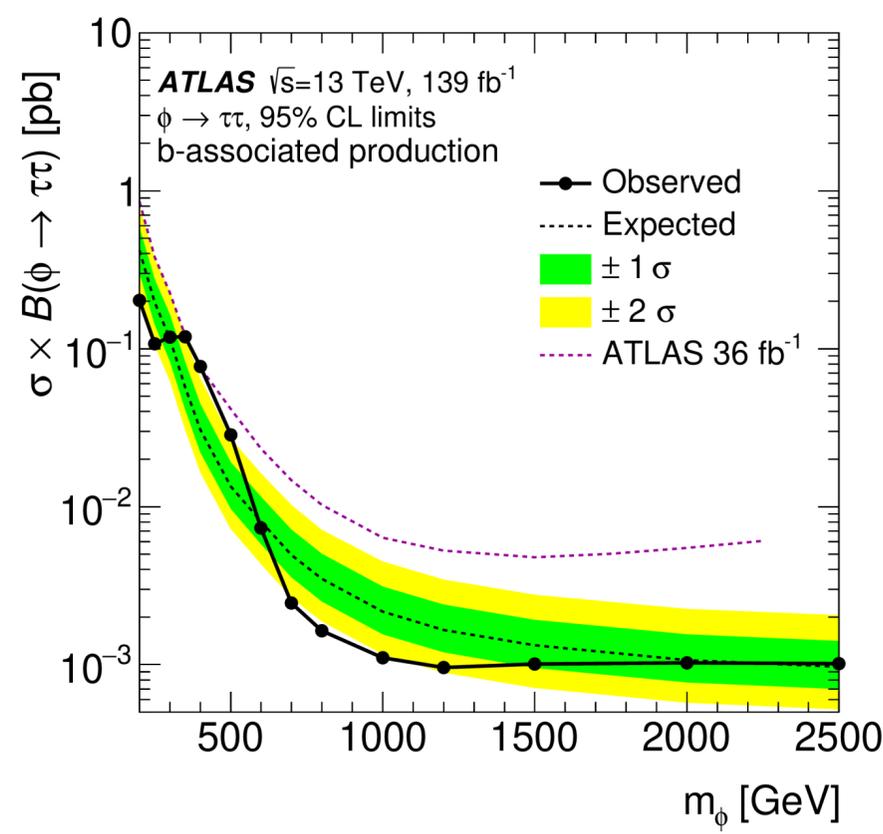
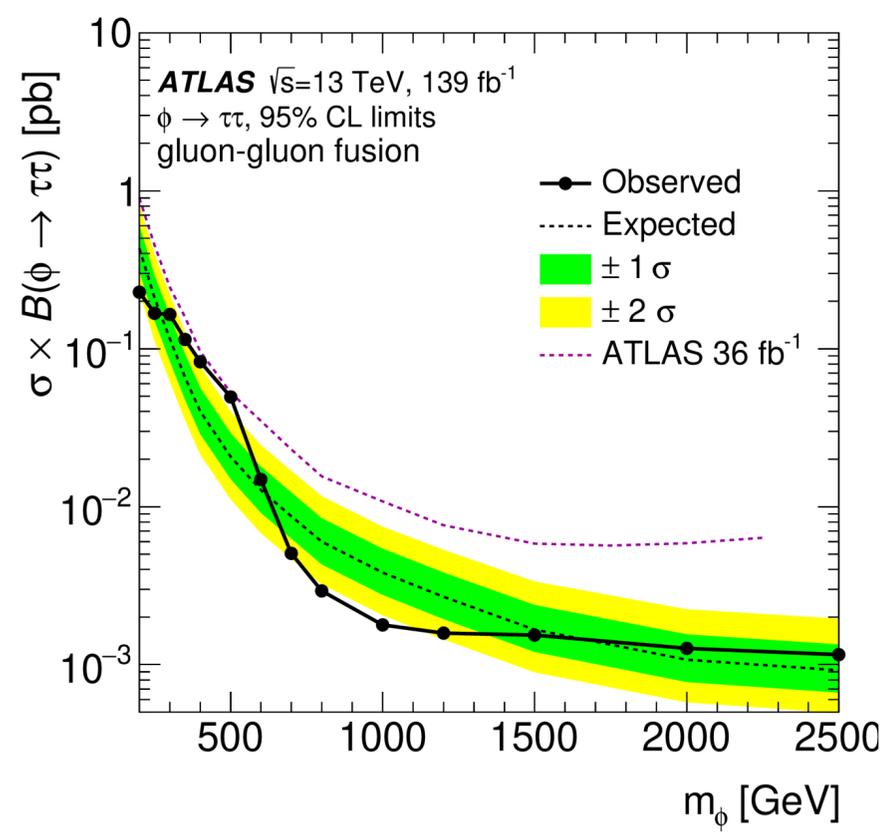
Neutral Higgs

Channel	ATLAS	CMS	Probed mass range
$H/A \rightarrow \tau\tau$	139 fb ⁻¹ : PRL 125(2020)051801	36 fb ⁻¹ : JHEP 09(2018)007	90 GeV - 3.2 TeV
$H/A \rightarrow bb$	28 fb ⁻¹ : PRD 102(2020)032004	36 fb ⁻¹ : JHEP 08(2018)113	300 GeV - 2 TeV
$H/A \rightarrow tt$	20 fb ⁻¹ : PRL 119(2017)191803 (8 TeV)	36 fb ⁻¹ : JHEP 04(2020)171	400 - 750 GeV
$H/A \rightarrow \mu\mu$	36 fb ⁻¹ : JHEP 07(2019)117	36 fb ⁻¹ : PLB 798(2019)134992	130 GeV - 1 TeV
$H/A \rightarrow \gamma\gamma$	139 fb ⁻¹ : ATLAS-CONF-2020-037 80 fb ⁻¹ : ATLAS-CONF-2020-025	20 + 3 fb ⁻¹ : PRL 117(2016)051802 20+35 fb ⁻¹ : PLB 793(2019)320	200 GeV - 3 TeV 65 GeV - 110 TeV
$A \rightarrow Zh_{SM}$	139 fb ⁻¹ : ATLAS-CONF-2020-043	36 fb ⁻¹ : JHEP 03(2020)065	300 GeV - 2 TeV
$A \rightarrow ZH$ $H \rightarrow ZA$	139 fb ⁻¹ : ATLAS-HDBS-2018-13	36 fb ⁻¹ : JHEP 03(2020)055	A: 250 - 800 GeV H: 30 GeV - 1 TeV
$H \rightarrow ZZ$	139 fb ⁻¹ : arXiv:2009.14791	36 fb ⁻¹ : JHEP 06(2018)127	130 GeV - 3 TeV
$H \rightarrow WW$	36 fb ⁻¹ : EPJC 78(2018)24	36 fb ⁻¹ : JHEP 03(2020)034	200 GeV - 5 TeV

H/A → ττ

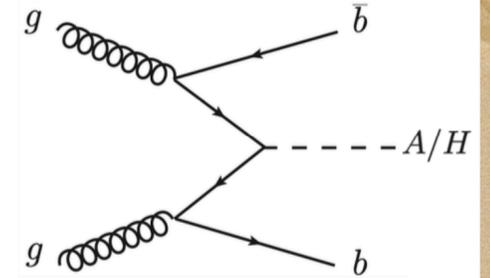
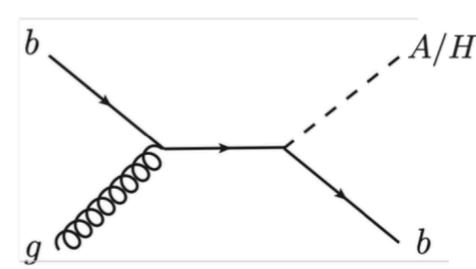
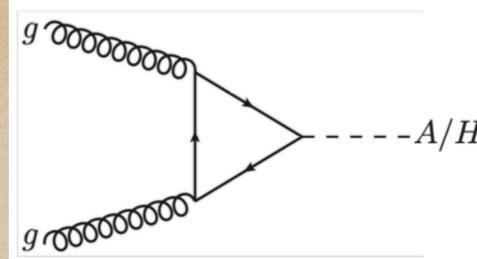


- ◆ Gluon fusion and associated production with b-quark
- ◆ Most sensitive decay channel where not suppressed, i.e. in type 2 of 2HDM for high $\tan\beta$
- ◆ Improvements due to increased luminosity, improved tau ID and optimization of analysis



The observed upper limits on the $\chi S^* BR(\phi)$ vs $m(\phi)$ and the fraction of b-associated production.

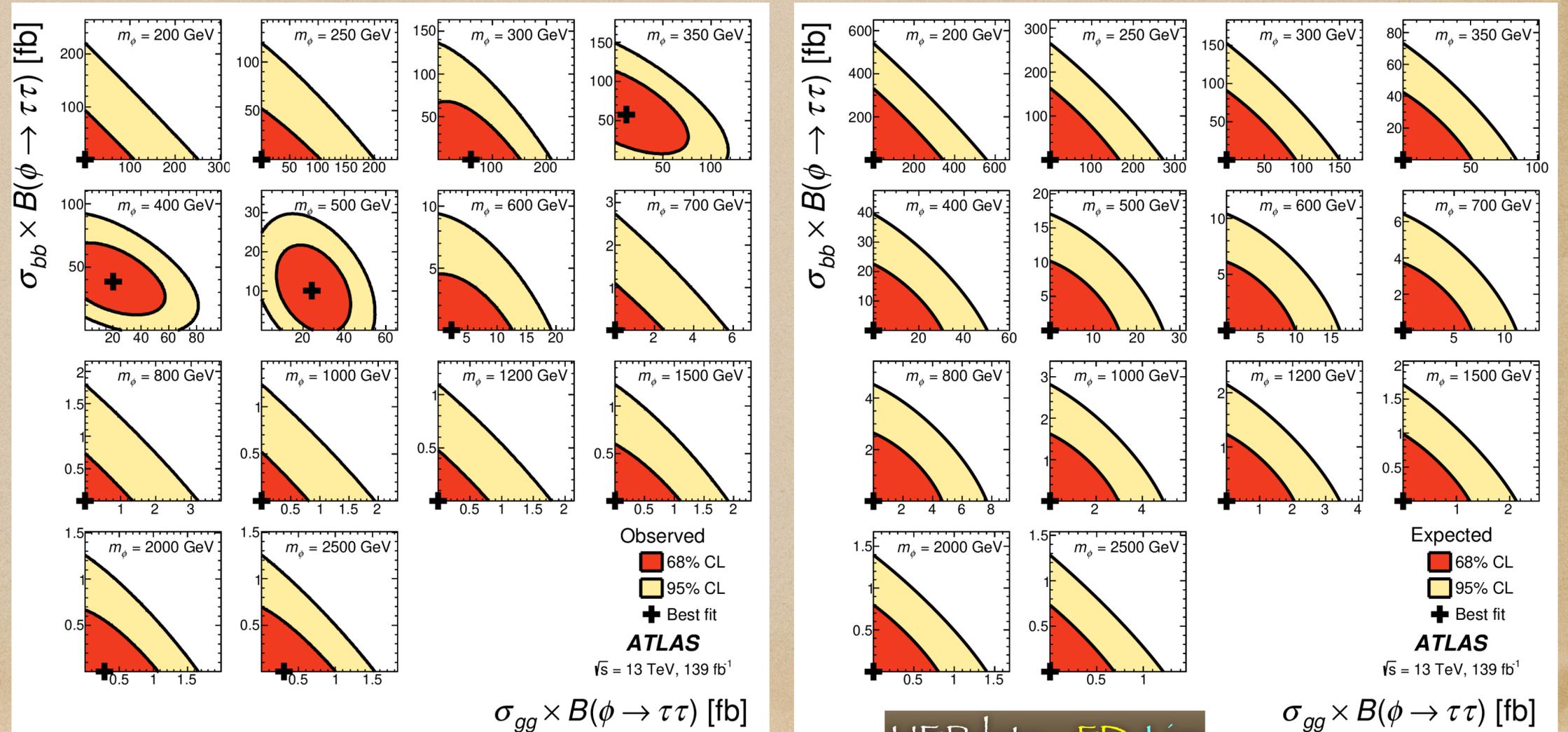
$$H/A \rightarrow \tau\tau$$



♦ Two dimensional likelihood scans of the $\sigma_{gg} \times B(\phi \rightarrow \tau\tau)$ vs $\sigma_{bb} \times B(\phi \rightarrow \tau\tau)$ for a given Higgs boson mass (m_ϕ).

♦ At each point $\Delta(\text{NLL})$ is calculated, defined as the negative-log-likelihood (NLL) of the conditional fit to the observed data with σ_{gg} and σ_{bb} fixed to their values at the point and with the minimum NLL value at any point subtracted.

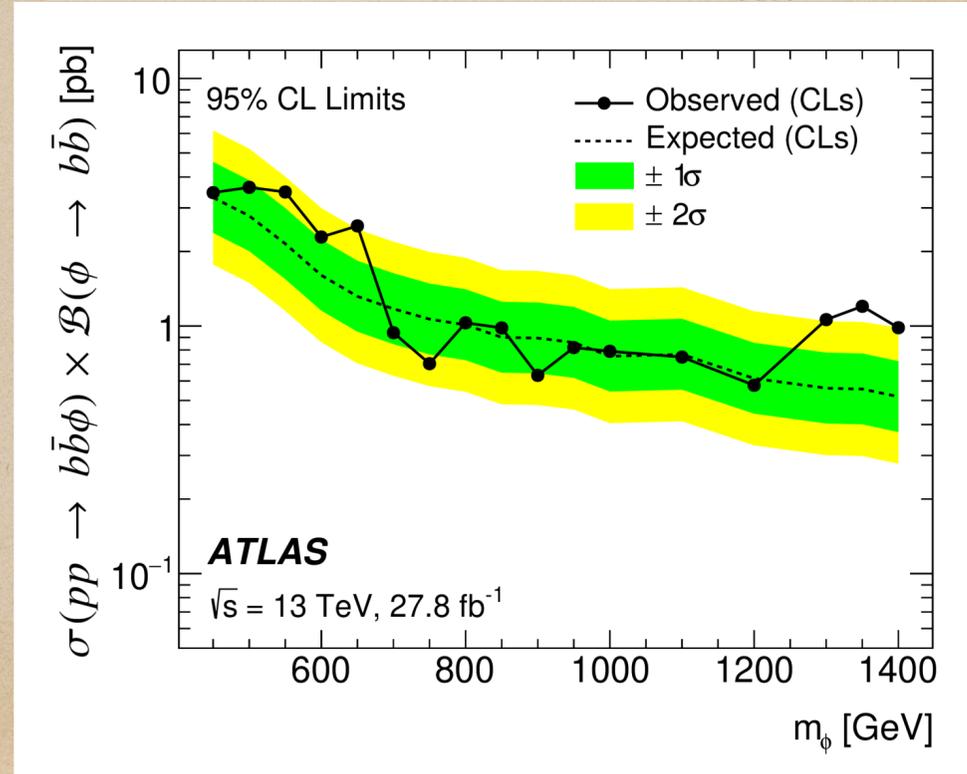
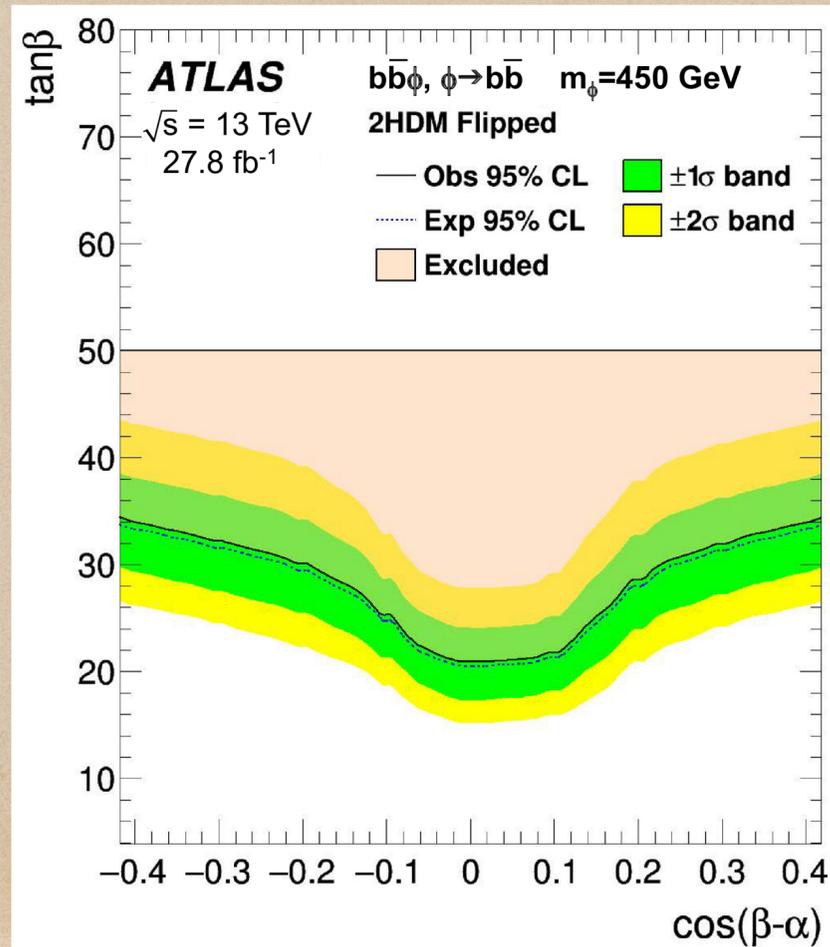
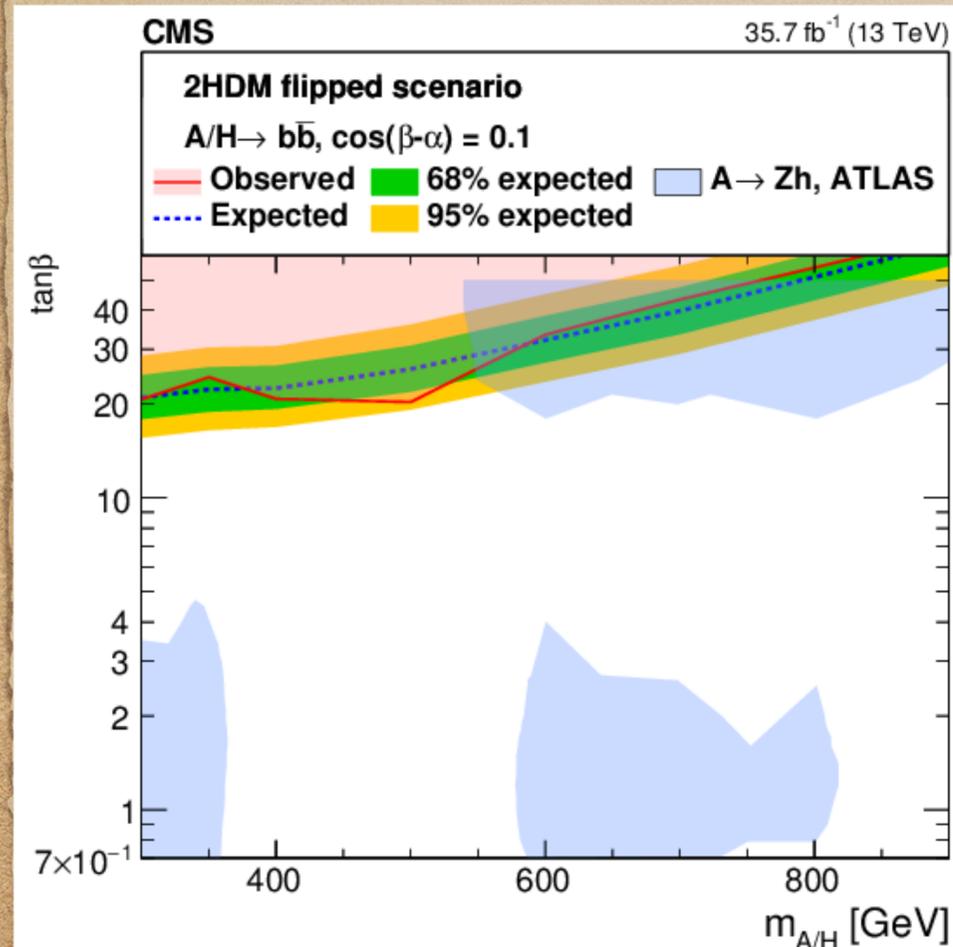
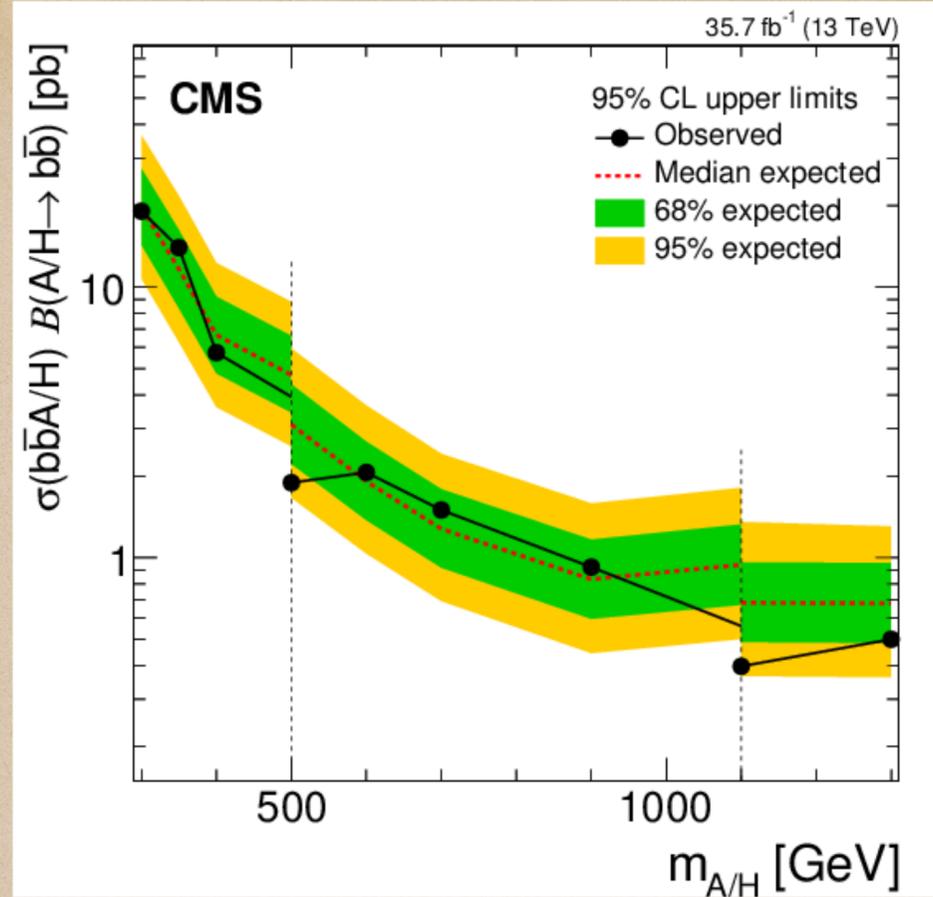
♦ The best-fit point, and the preferred 68% and 95% CL boundaries are found at $2\Delta(\text{NLL})$ values of 0.0, 2.30 and 5.90.





CMS - HEPdata - Lim

- ◆ Only associated production with b-quark
 - ◆ Still very difficult due to huge background and triggering
- ◆ Most sensitive in type 4 of 2HDM (flipped) - other models?

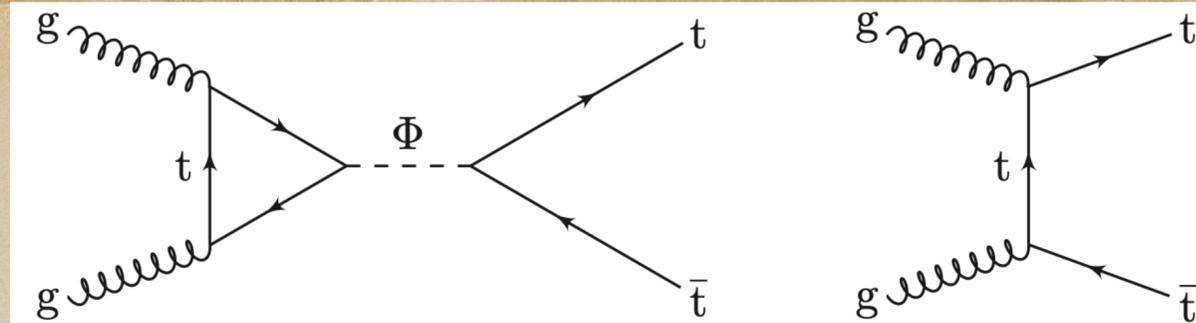


$$H/A \rightarrow t\bar{t}$$

- ◆ Gluon fusion production
- ◆ Suffers from interference effects => the signal consists of a resonant and an interference component
- ◆ Scanned relative total decay widths Γ_ϕ/m_ϕ : 2.5, 5, 10, 25%

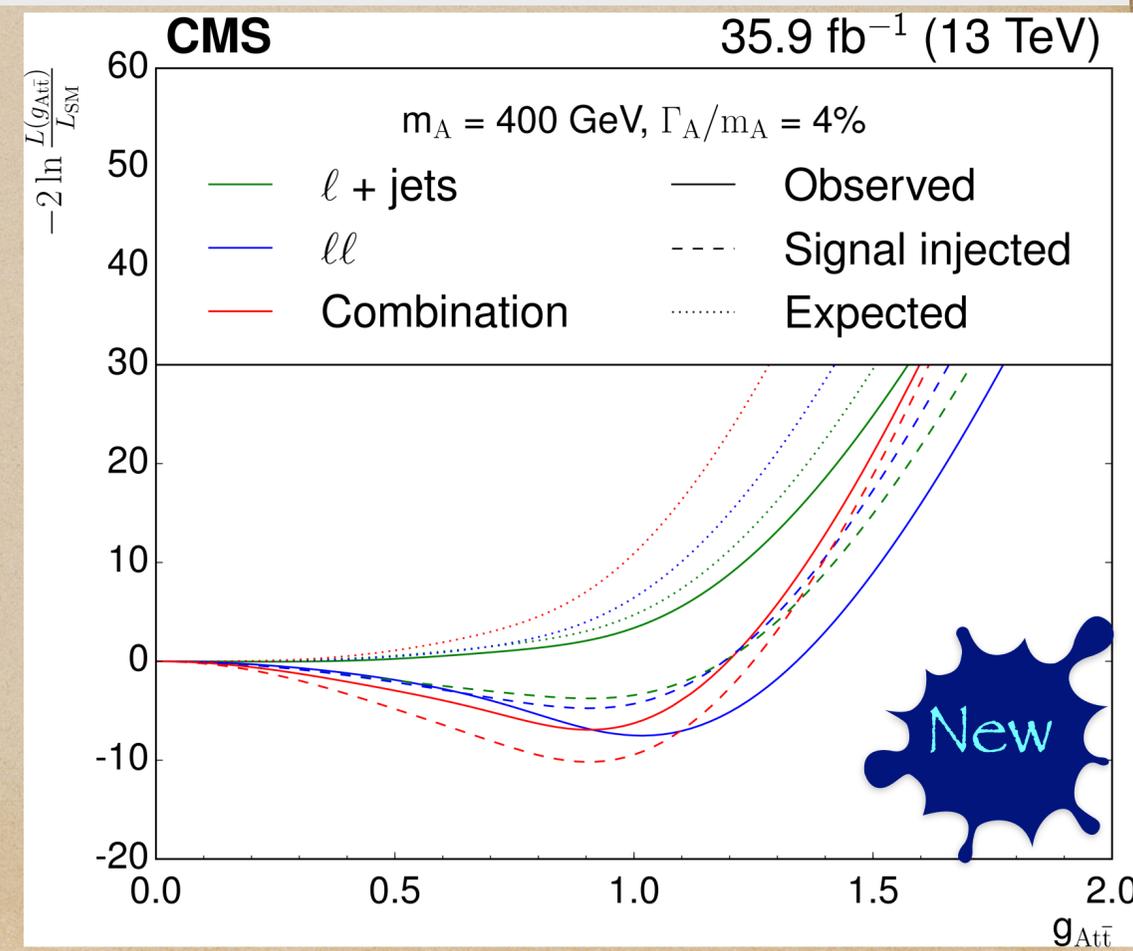
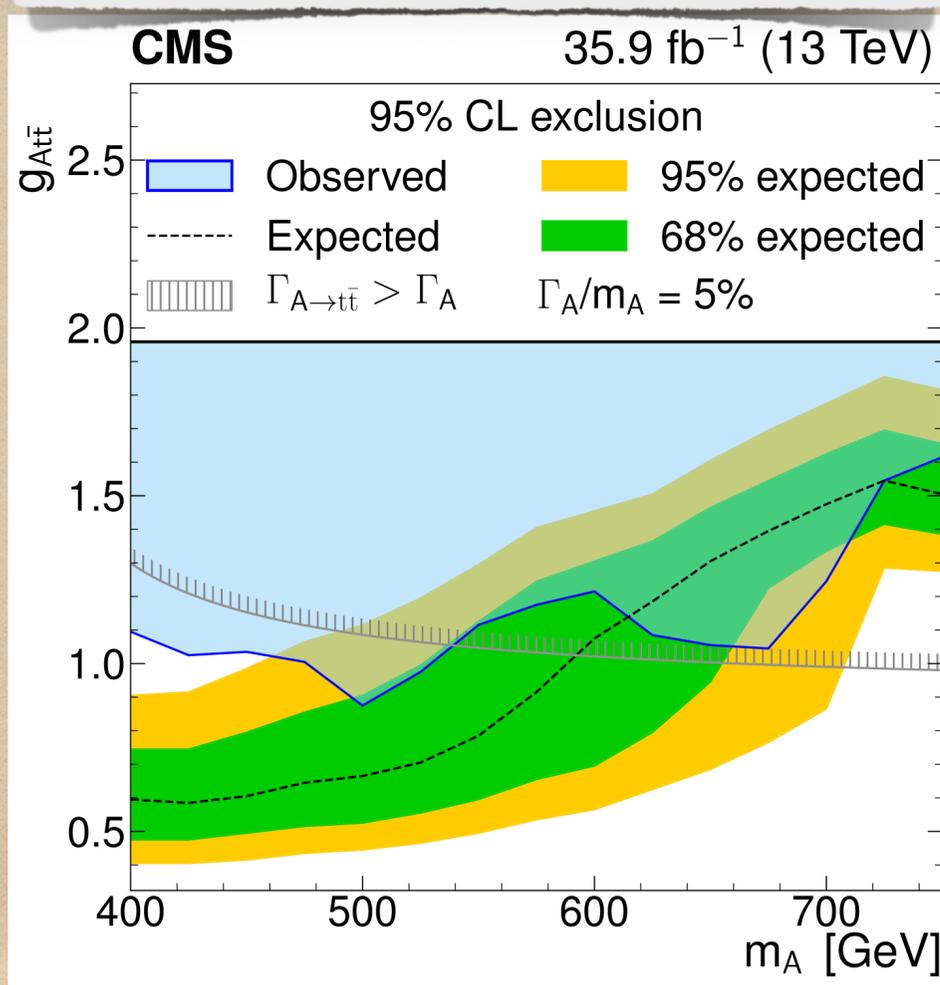
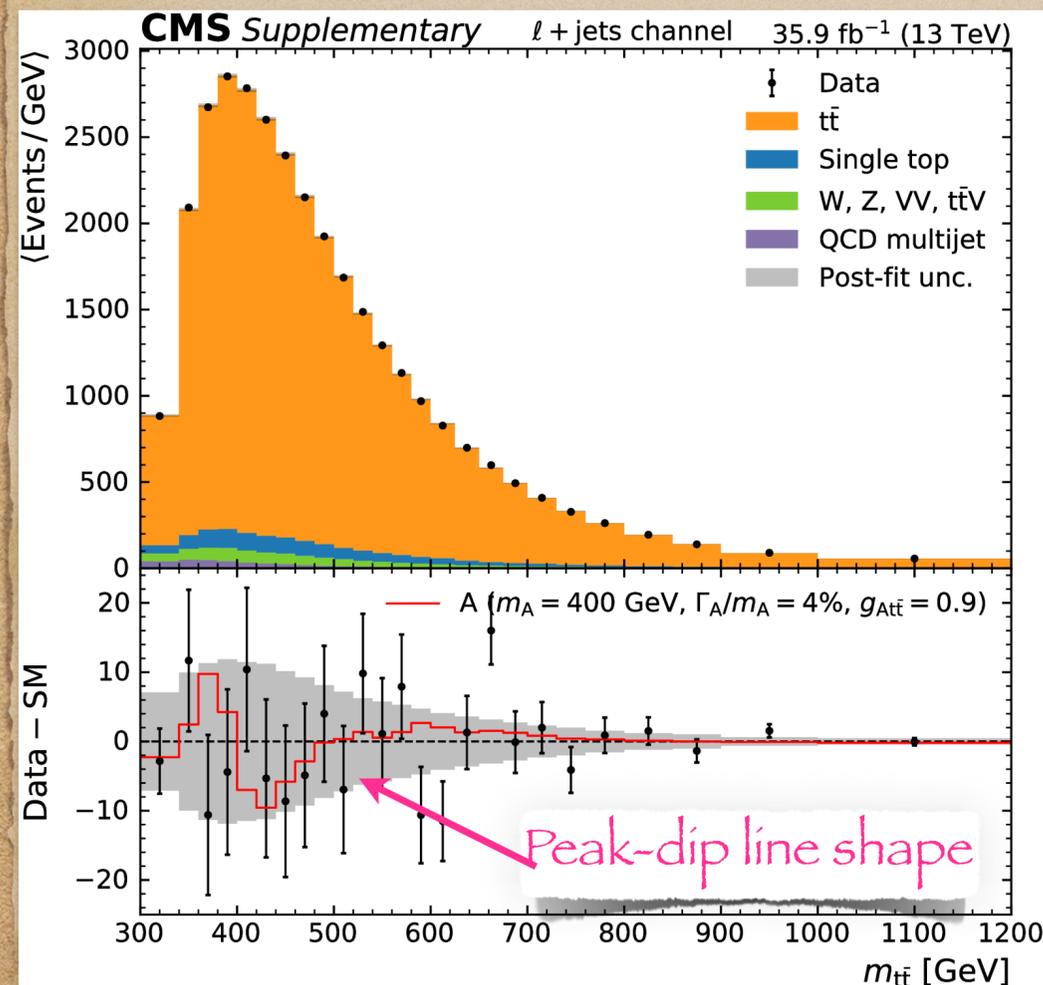
HEPdata - Lim

Model-independent constraints on the $g_{A(H)tt}$ for different relative widths



Global (local) significance of the excess is 1.9 (3.5) sd (global p-value of 0.028)

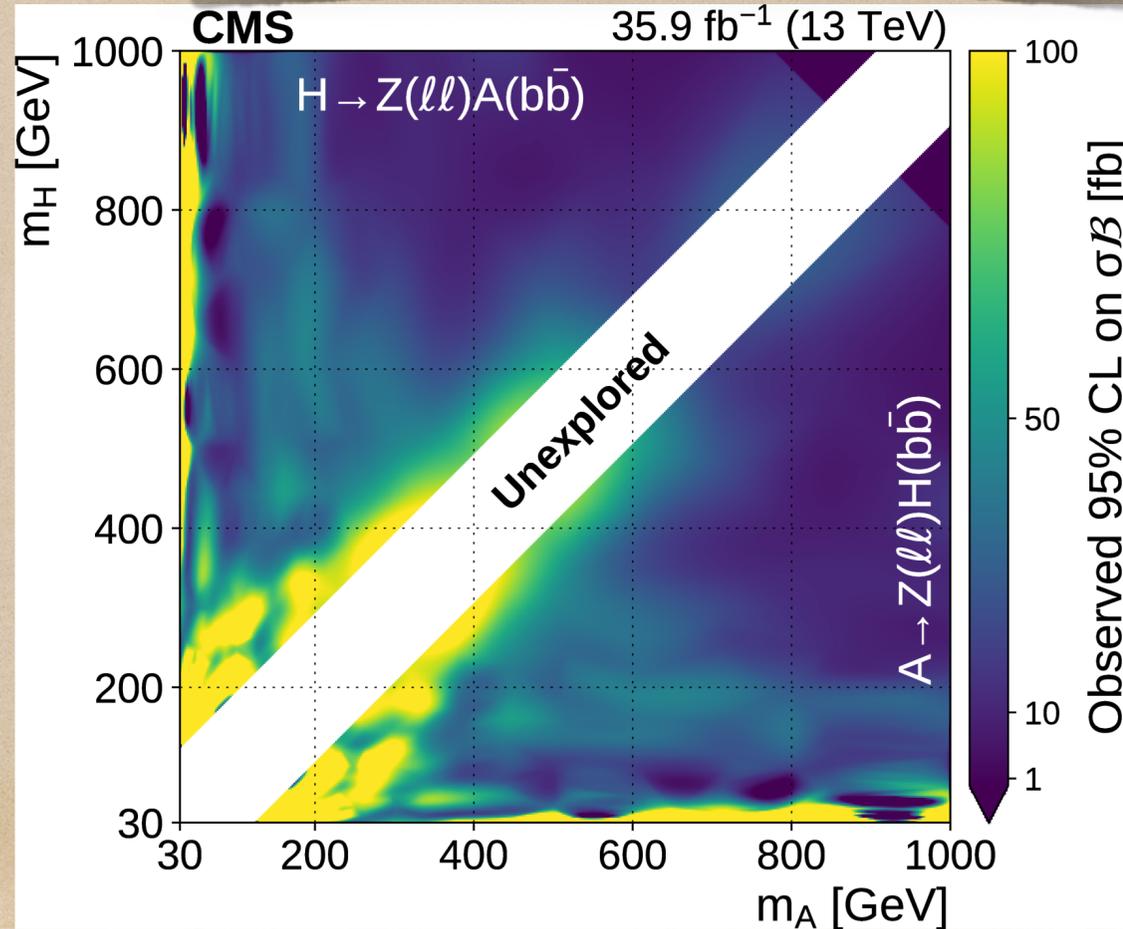
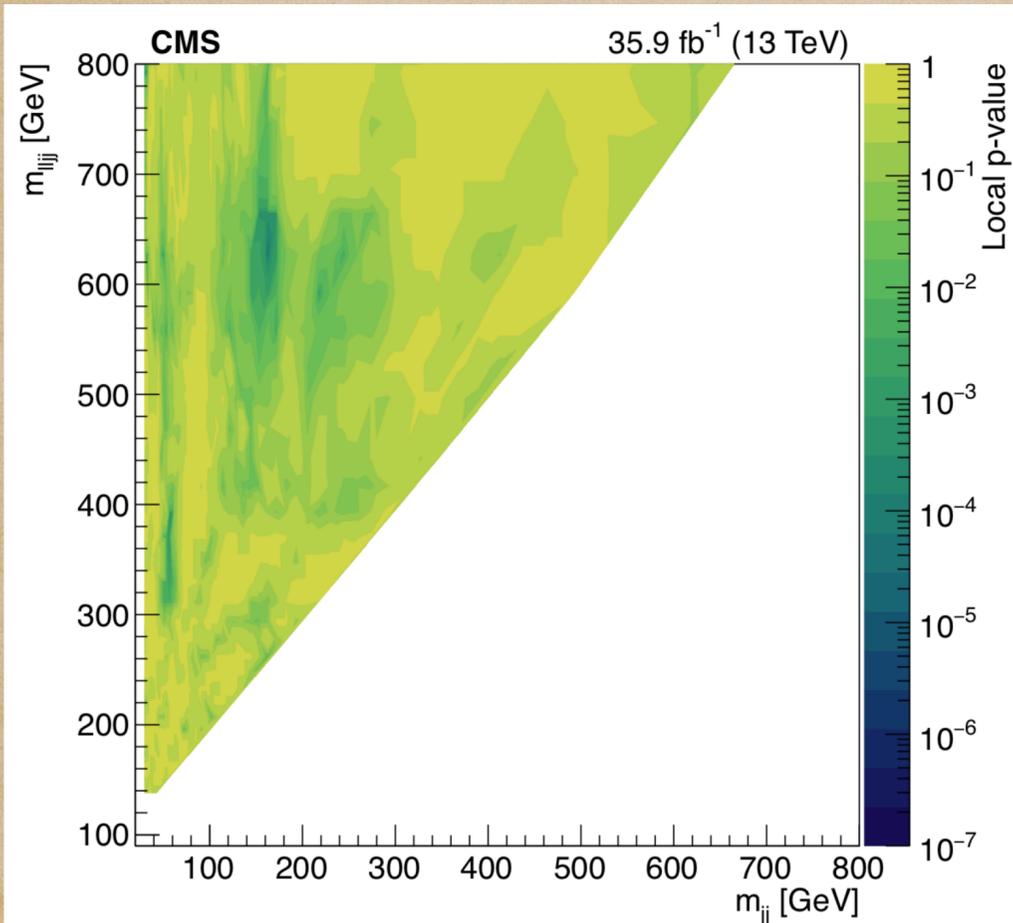
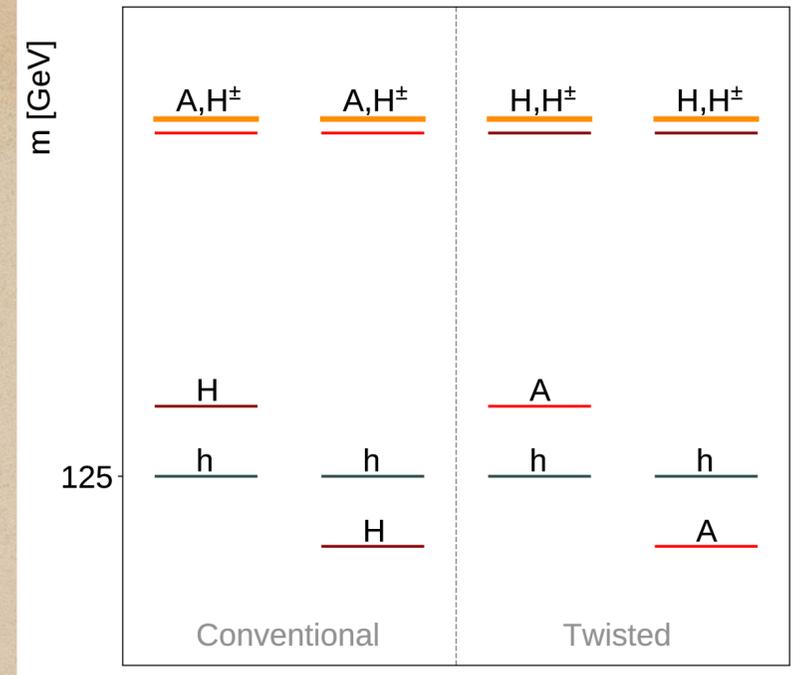
Can be due to the higher-order (NNLO) electroweak corrections to the SM $t\bar{t}$ production in the vicinity of the pair production threshold



$A \rightarrow ZH$ and $H \rightarrow ZA$

- ◆ Final states with $H \rightarrow bb$ and $H \rightarrow WW$ (ATLAS)
- ◆ Investigated both cases, $m_A > m_H$ and $m_H > m_A$ (CMS)
- ◆ Interesting for interpretation

CMS: Largest local (global) deviation
 3.9sd (1.3 sd) for $(m_A, m_H) = (630, 160)$ GeV



ATLAS (bb): Largest local (global) deviation 3.1sd (1.3 sd) for $(m_A, m_H) = (610, 290)$ GeV



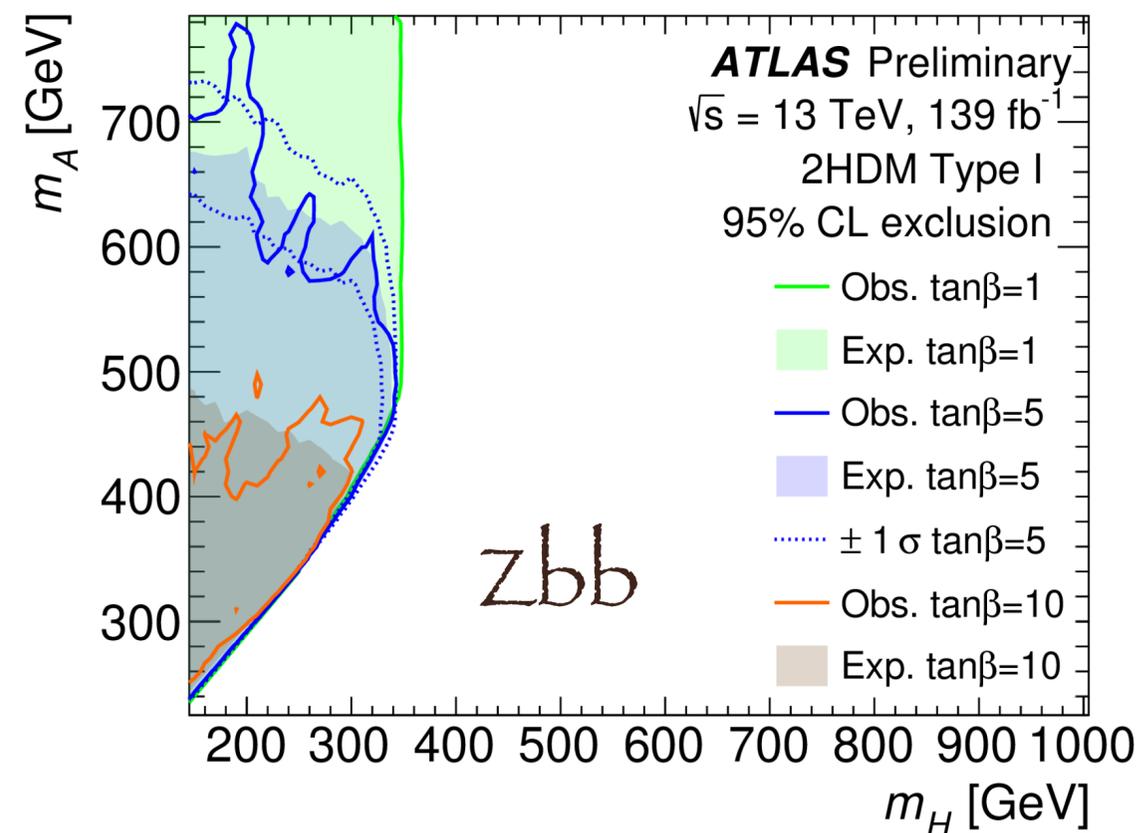
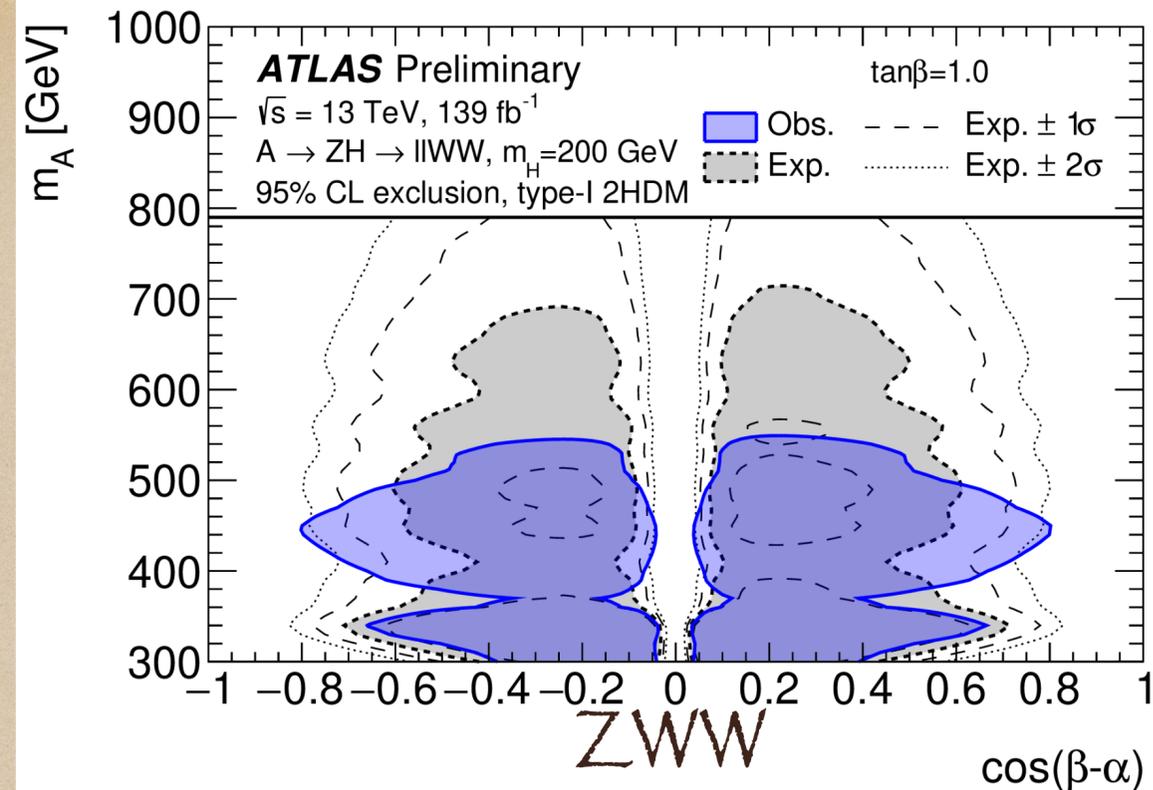
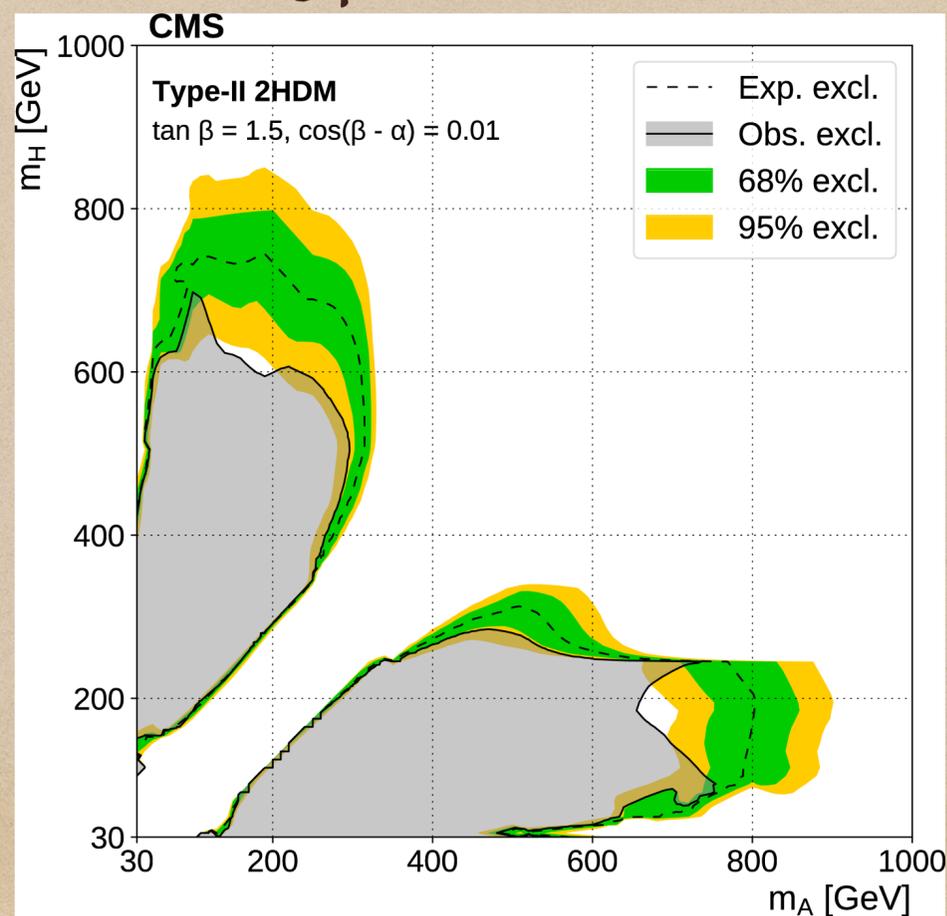
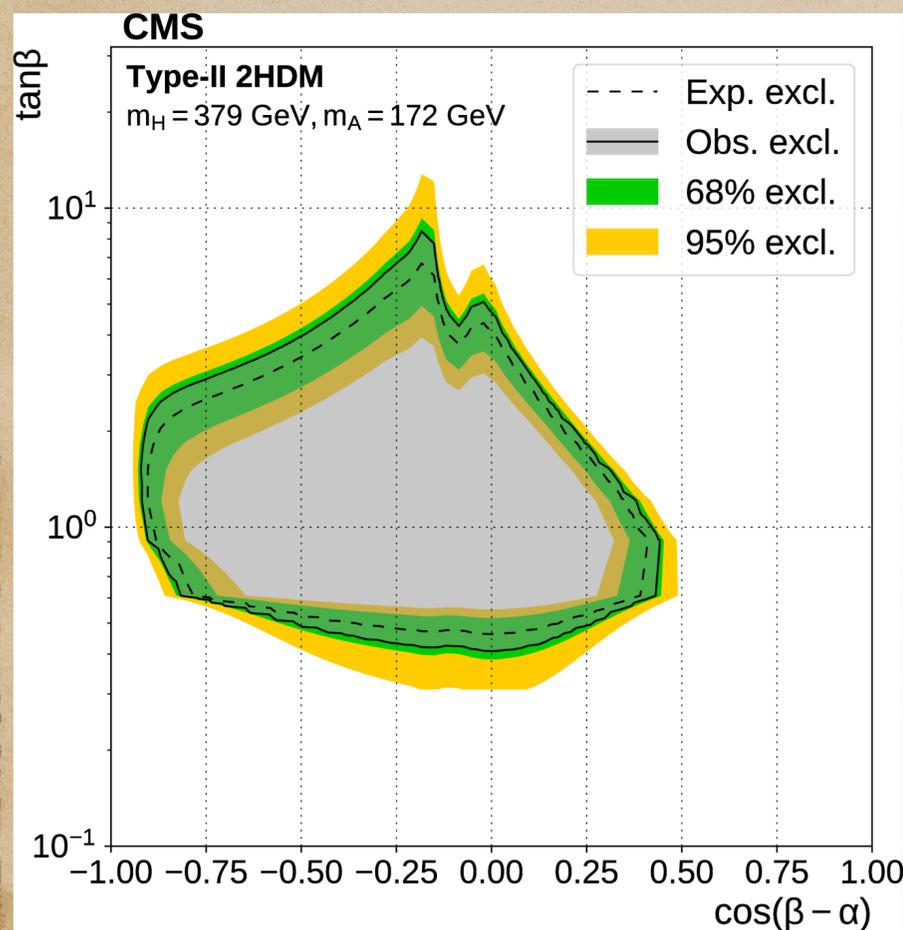
$A \rightarrow ZH$ and

$H \rightarrow ZA$



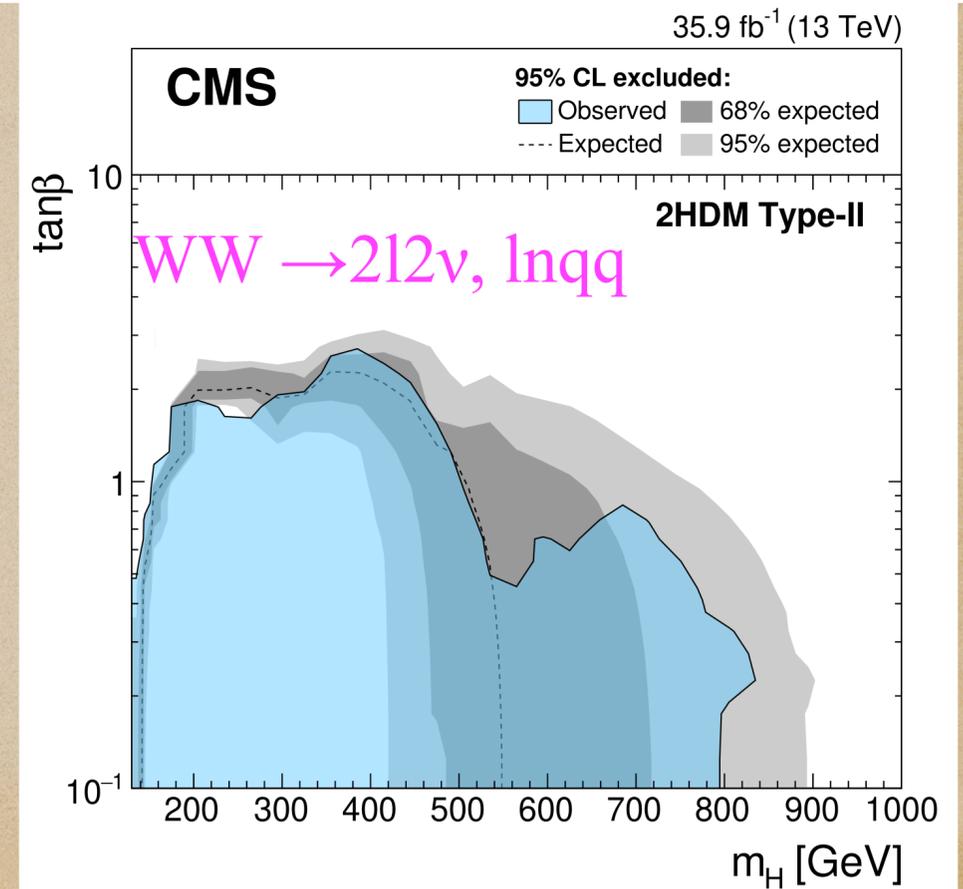
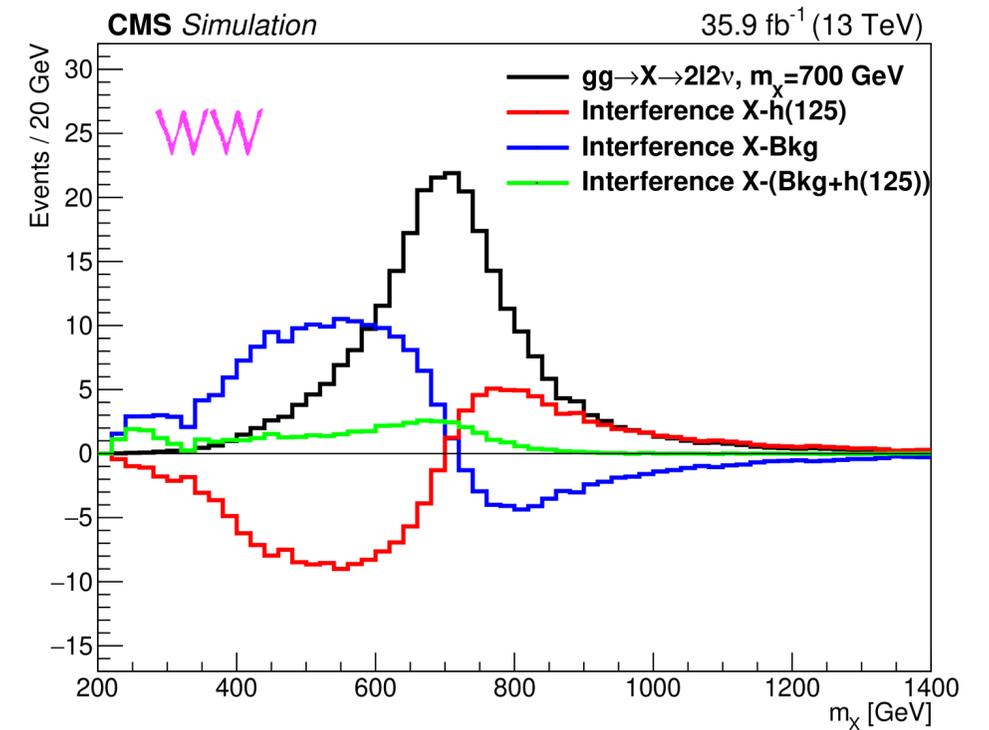
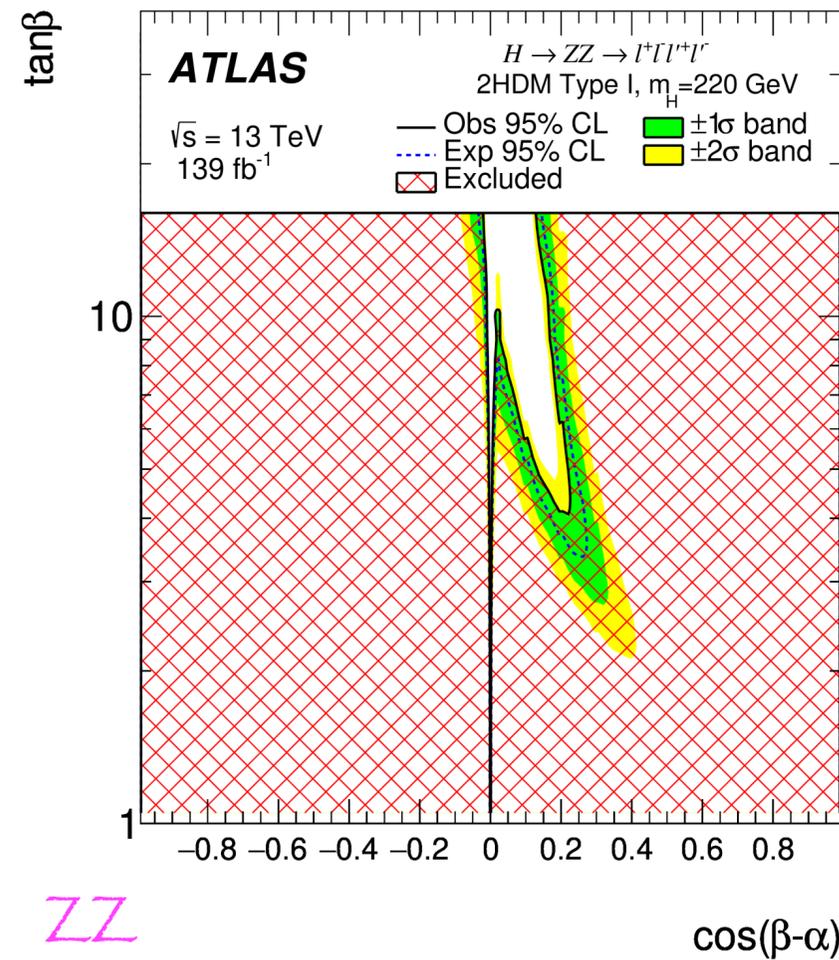
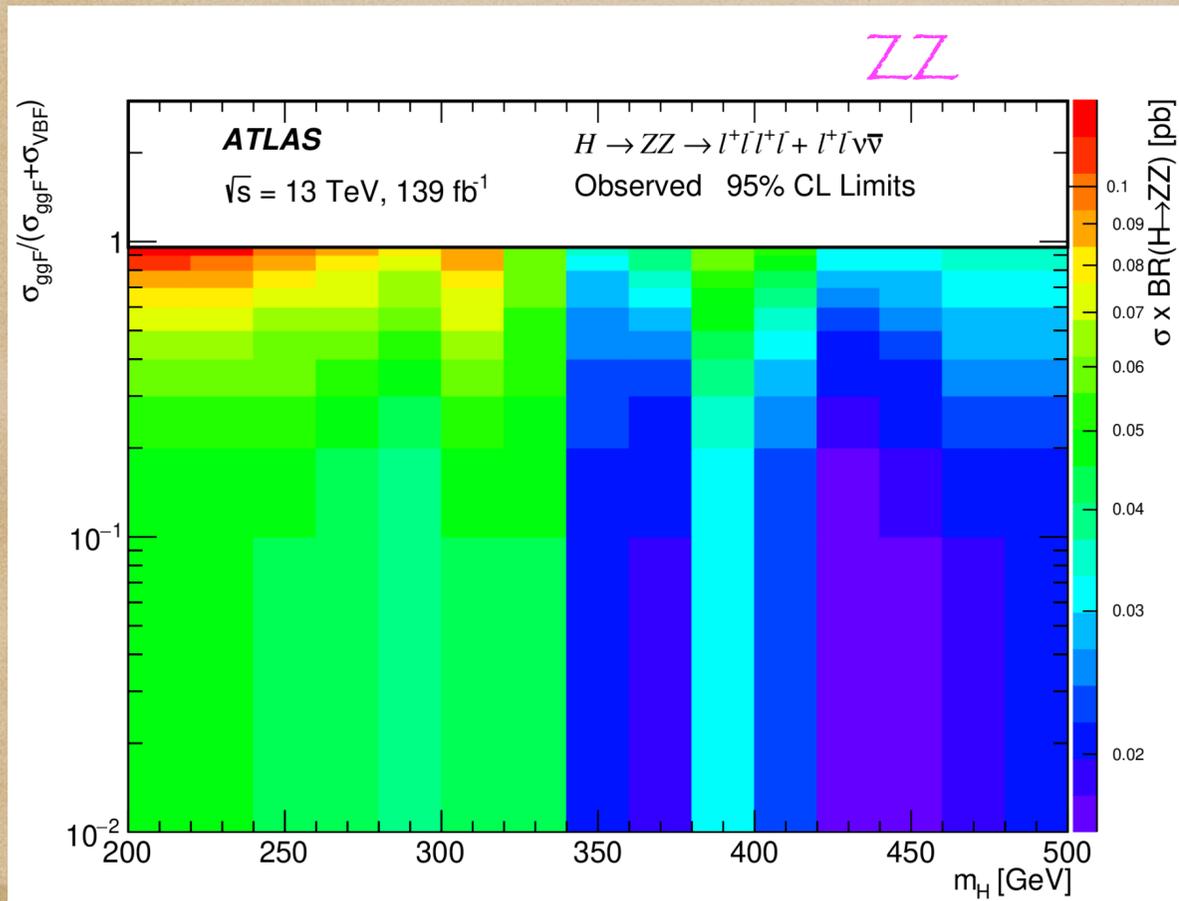
CMS - HEPdata - FD, Lim

- ◆ Interpreted in 2HDM
- ◆ CMS in type 2
- ◆ ATLAS all four for bb and type 1 and 3 for WW



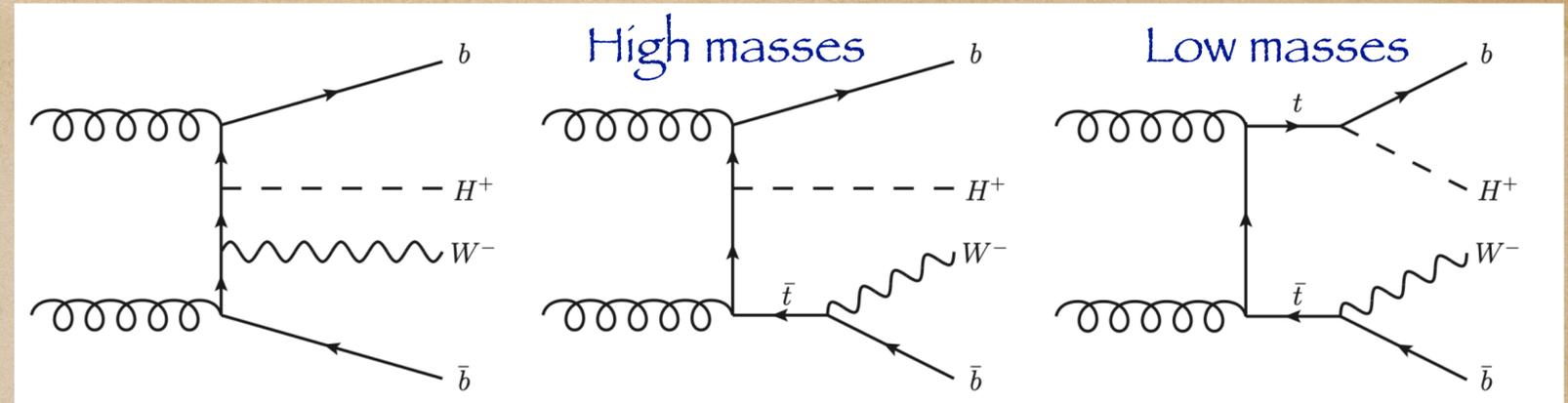
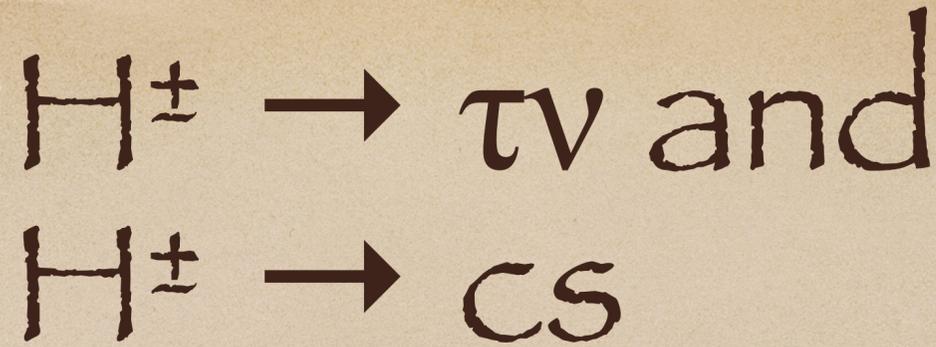
$H \rightarrow ZZ$ and $H \rightarrow WW$

- ◆ Searched for in gluon fusion and VBF production modes with different width assumptions and included interference effects
- ◆ Interpreted in various 2HDM, but also in Georgi-Machacek model ($ATLAS$ VBF $H \rightarrow WW$)



Charged Higgs

Channel	ATLAS	CMS	Probed mass range
$H^\pm \rightarrow \tau\nu$	36 fb ⁻¹ : <u>JHEP 09(2018)139</u>	36 fb ⁻¹ : <u>JHEP 07(2019)142</u>	80 GeV - 3 TeV
$H^\pm \rightarrow tb$	139 fb ⁻¹ : <u>ATLAS-CONF-2020-039</u>	36 fb ⁻¹ : <u>JHEP 07(2020)126</u> , 36 fb ⁻¹ : <u>JHEP 01(2020)096</u>	200 GeV - 3 TeV
$H^\pm \rightarrow cs$	5 fb ⁻¹ : <u>EPJC 73(2013)2465</u> (8 TeV)	36 fb ⁻¹ : <u>PRD 102(2020)072001</u>	200 GeV - 2 TeV
$H^\pm \rightarrow WZ$	36 fb ⁻¹ : <u>PLB 787(2018)68</u>	36 fb ⁻¹ : <u>PLB 798(2019)134985</u> , <u>PLB 795(2019)281</u>	600 GeV - 2 TeV
$H^\pm \rightarrow Wh/H/A$	20 fb ⁻¹ : <u>PRD 89(2014)032002</u> (h _{SM} , 8 TeV)	36 fb ⁻¹ : <u>PRL 123 (2019)131802</u>	H [±] : 100 - 160 GeV A: 5 - 75 GeV
H ^{±±}	139 fb ⁻¹ : <u>ATLAS-CONF-2020-056</u> 36 fb ⁻¹ : <u>EPJC 78(2018)199</u>	36 fb ⁻¹ : <u>PRL 120(2018)081801</u> 36 fb ⁻¹ : <u>PLB 798(2019)134985</u>	200 GeV - 2 TeV



- Searches for lower and higher ($\tau\nu$) masses

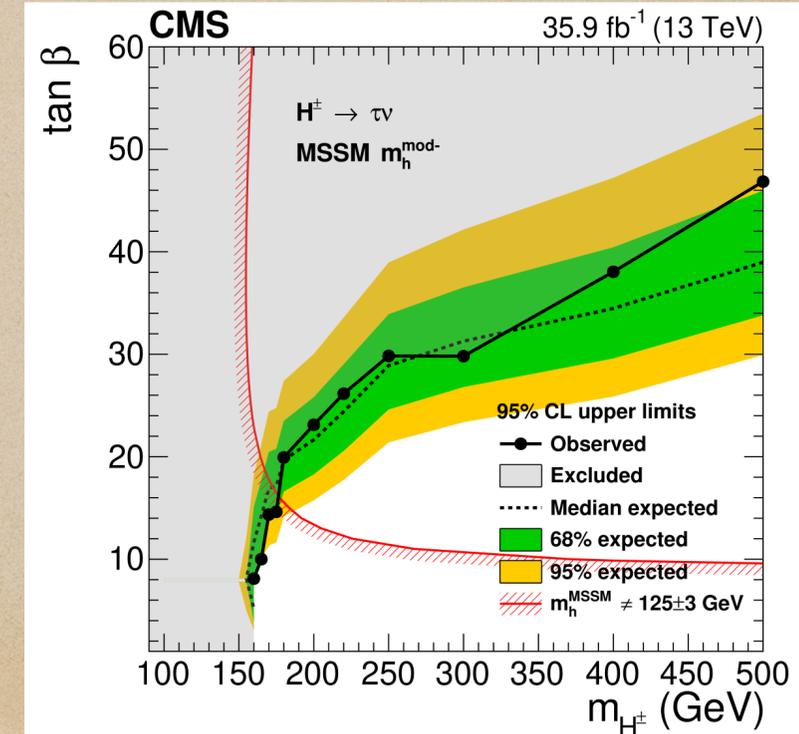
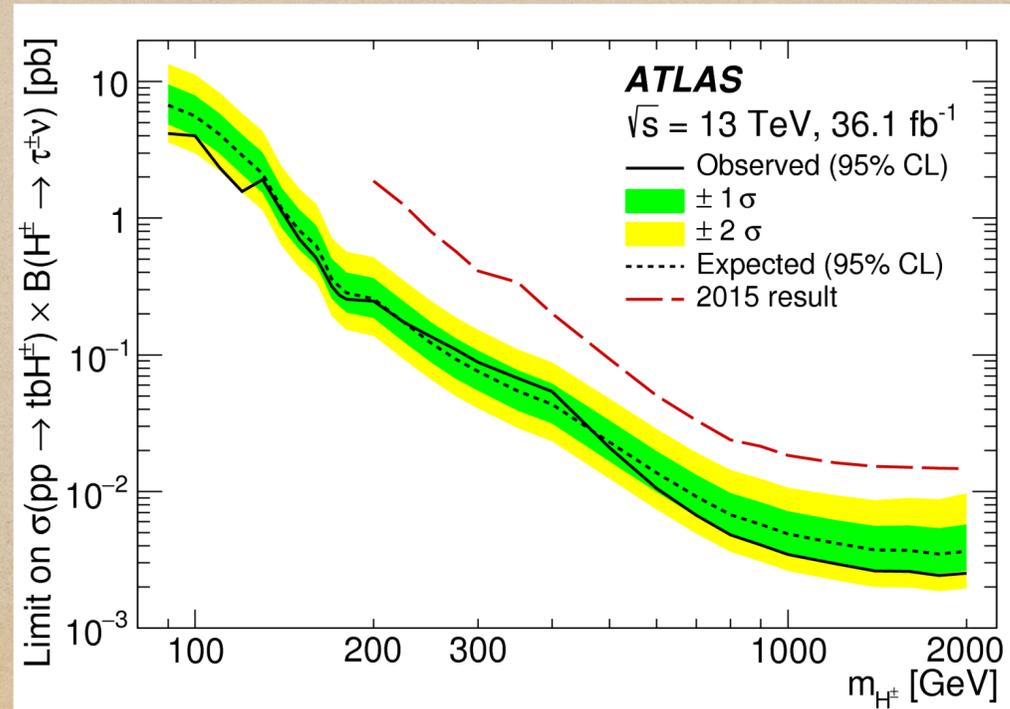
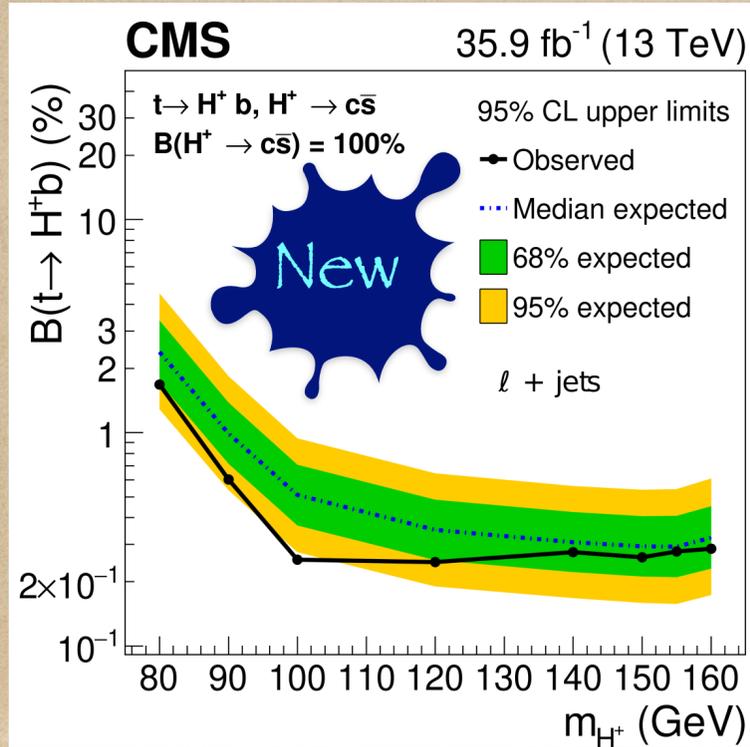
- Production with a top quark

- Interference between diagrams most relevant in the intermediate mass region

- Developing charm tagging opens exciting possibility of other final states with a c-quark

- Interpreted in MSSM, but many exciting interpretations are possible

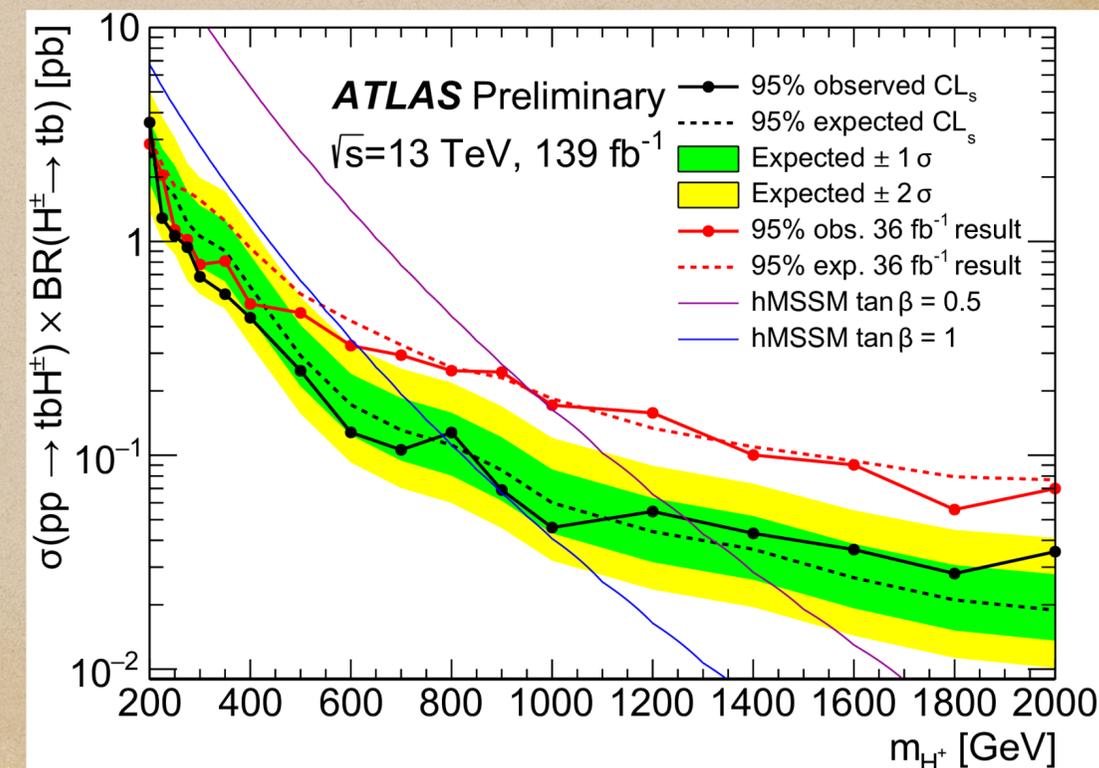
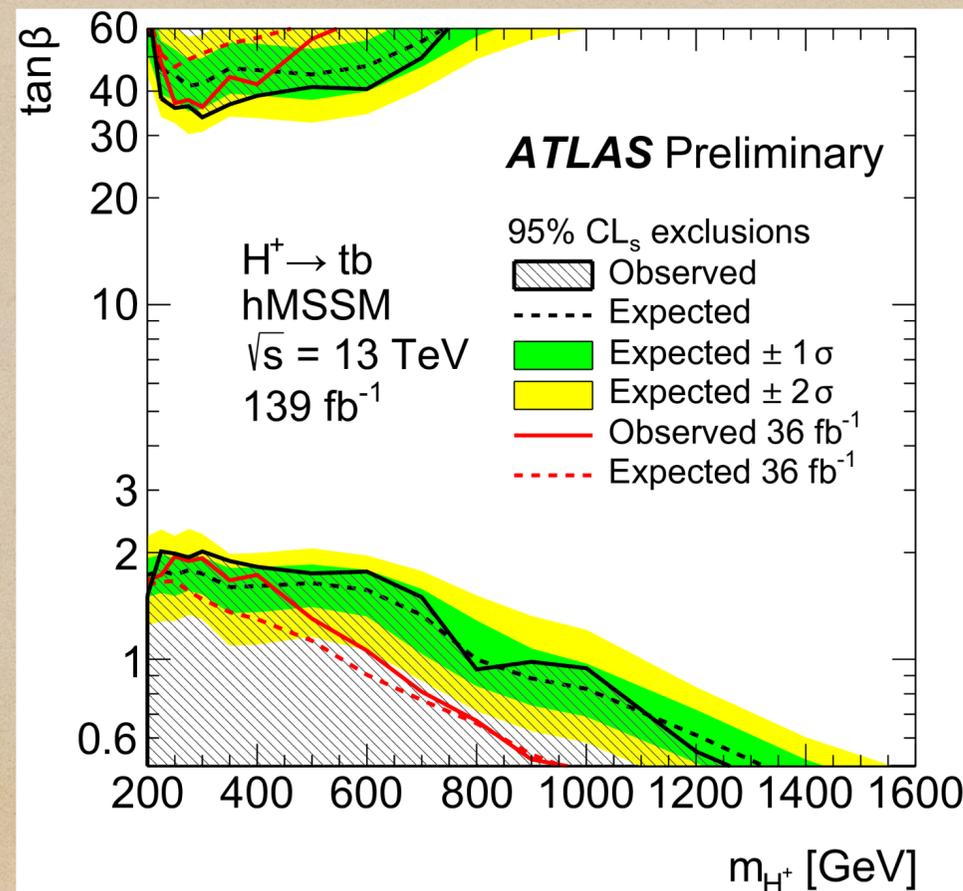
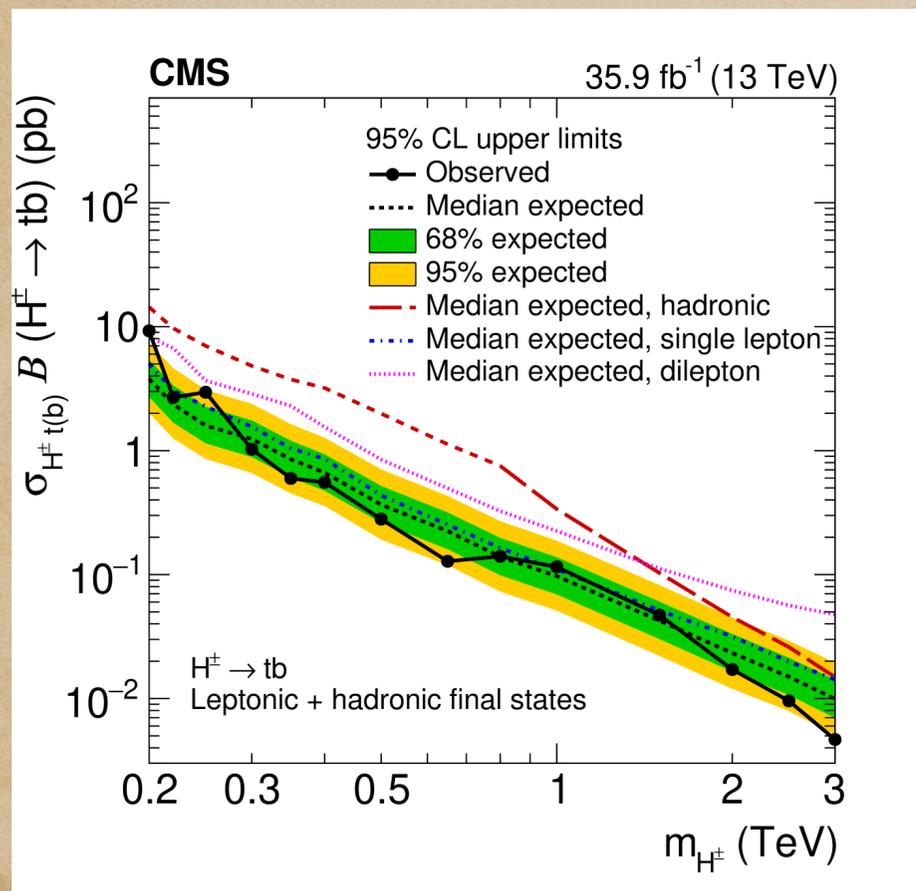
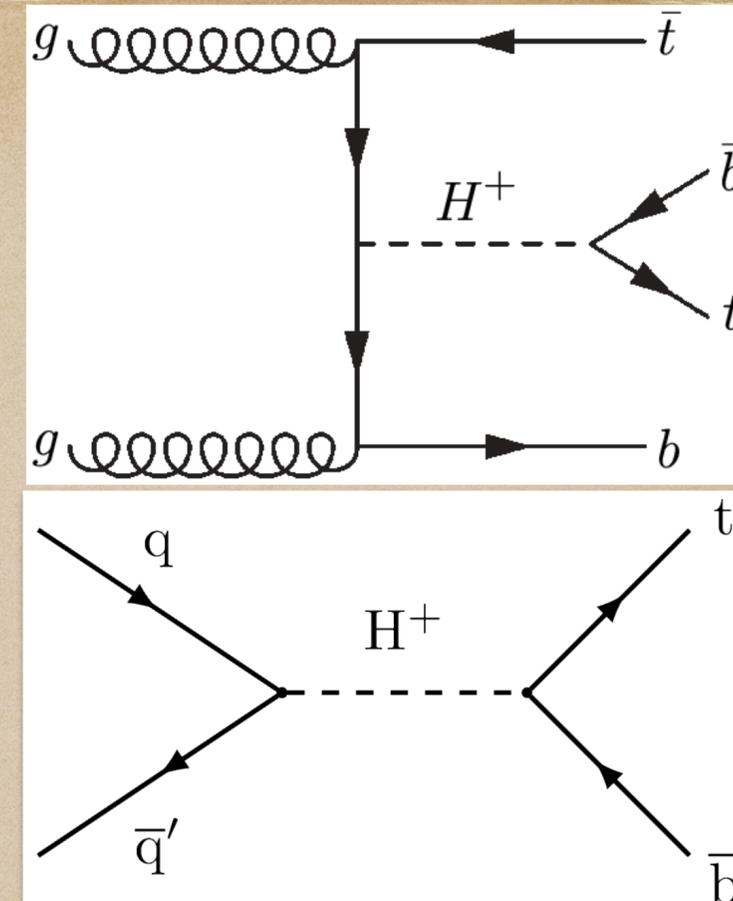
ATLAS, CMS ($\tau\nu$), CMS ($c\bar{s}$) - HEPdata - Lim

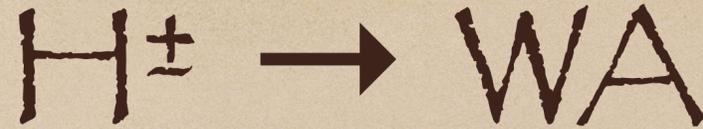




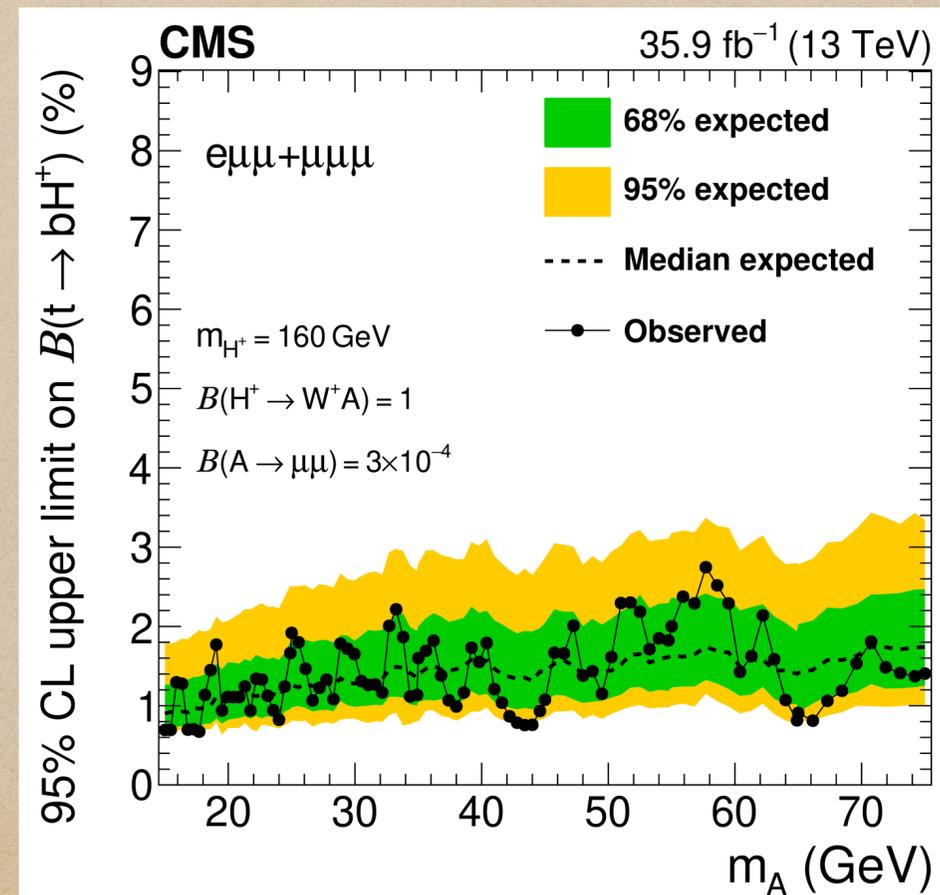
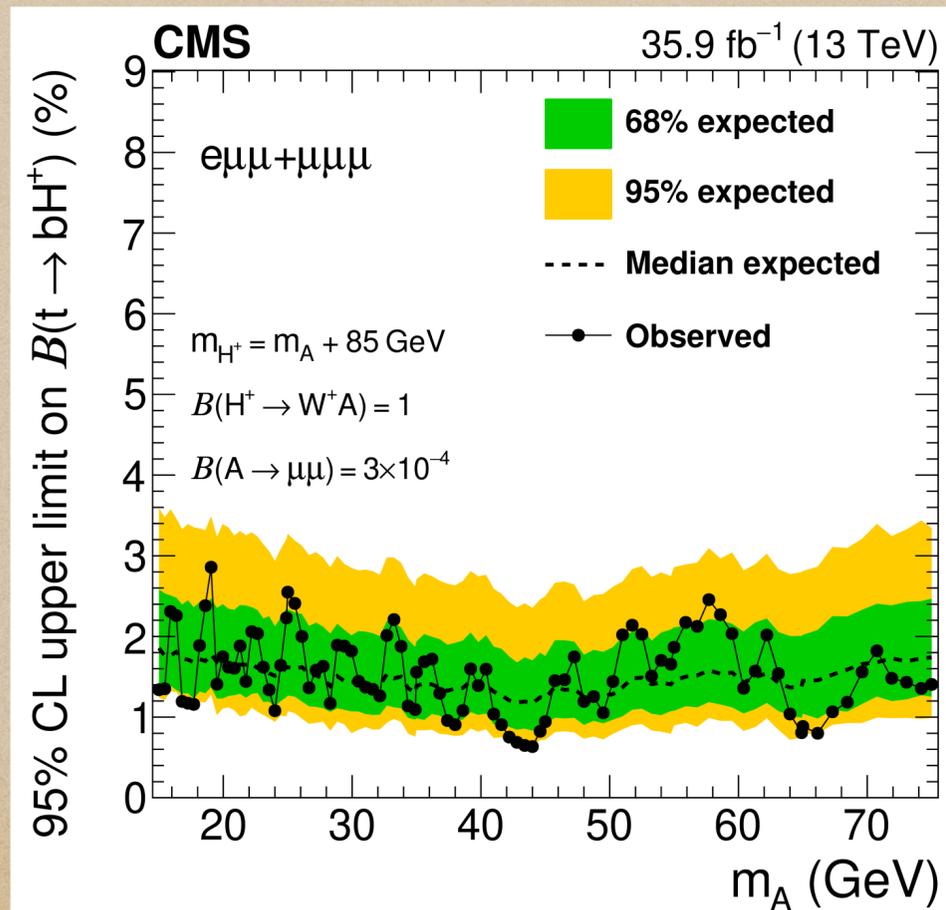
CMS (had), CMS (lep) - HEPdata - Lim

- Production in association with a top quark, but also in s-channel (CMS, all-had)
- Interpreted in MSSM - unique sensitivity to low and high $\tan\beta$





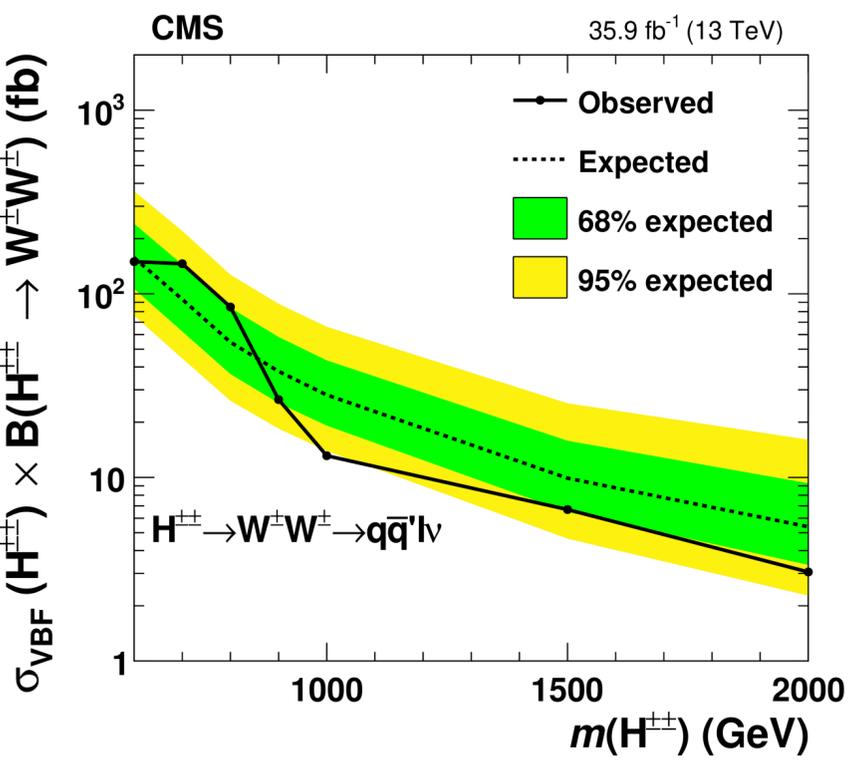
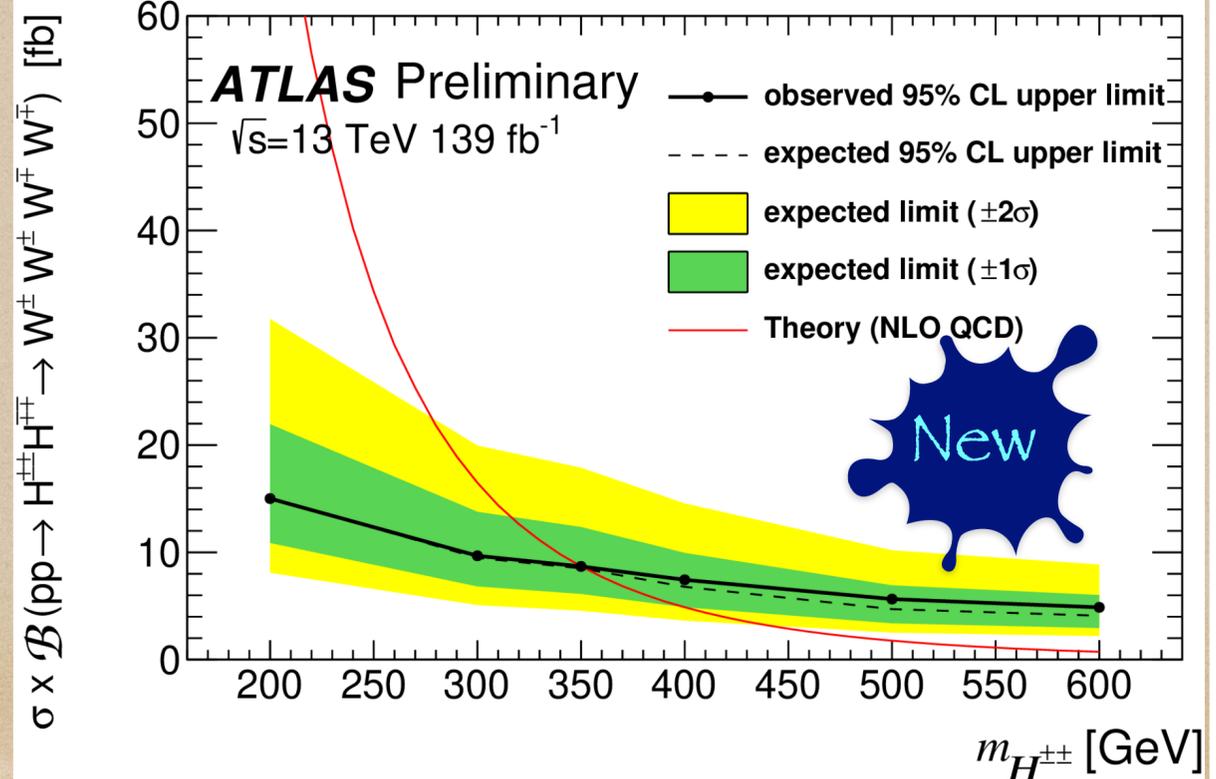
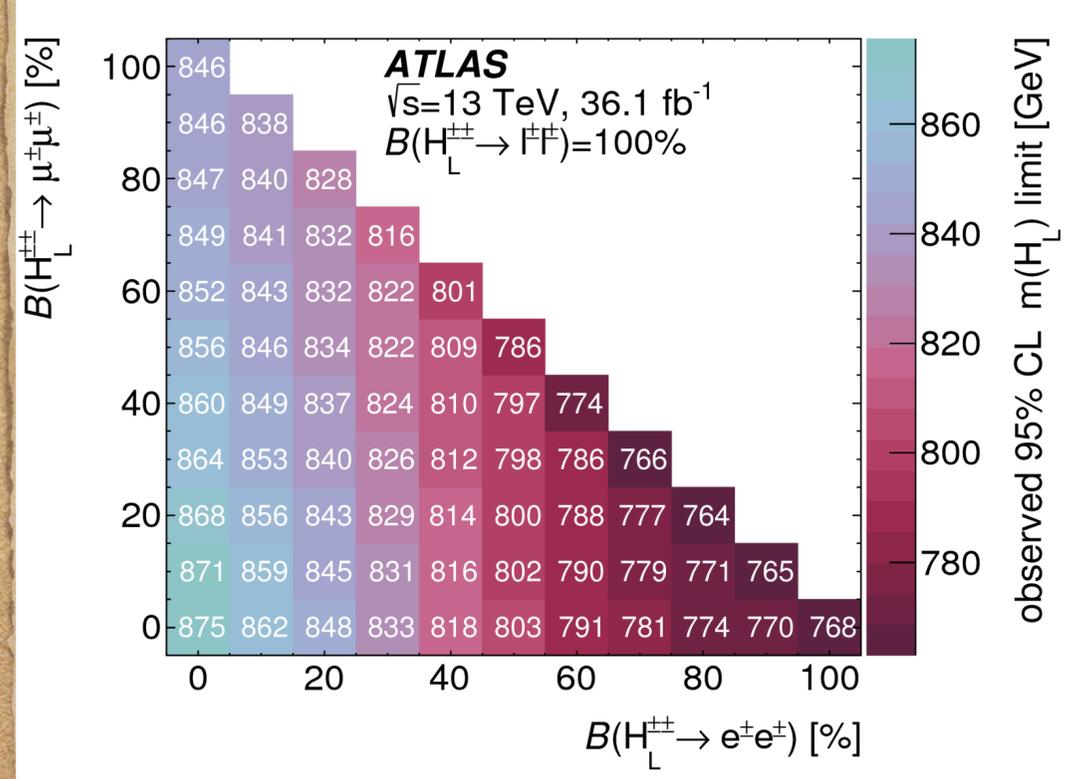
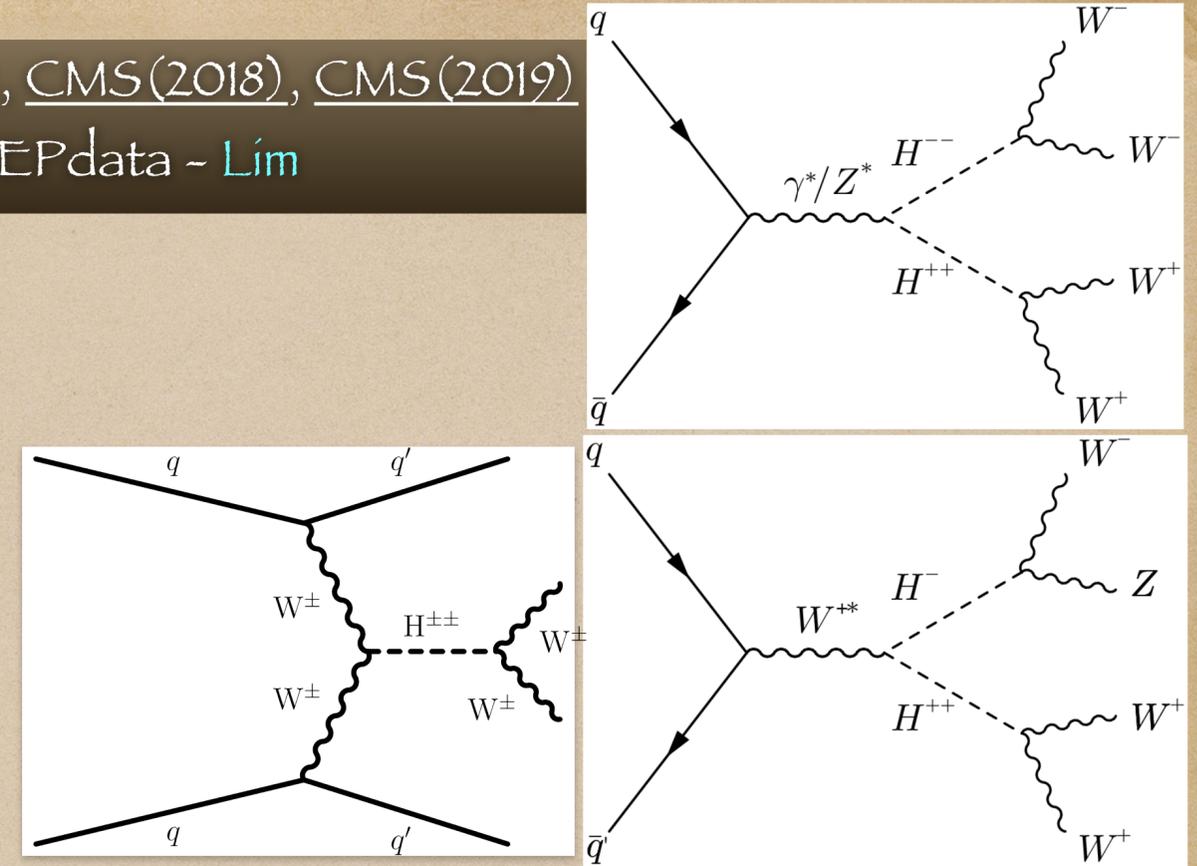
- ◆ Process (from top pair production): $t \rightarrow bH^\pm \rightarrow bW^\pm A \rightarrow bW^\pm \mu^+ \mu^-$
- ◆ Model independent interpretation



H^{±±}

ATLAS (multi-l), CMS(2018), CMS(2019)
 - HEPdata - Lim

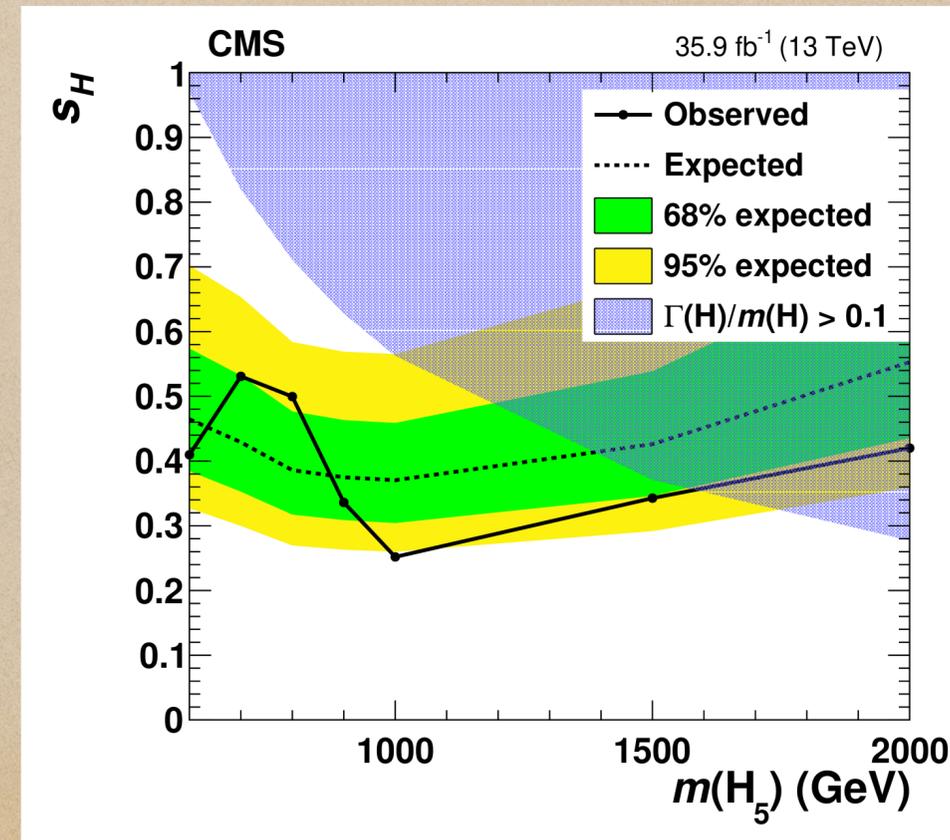
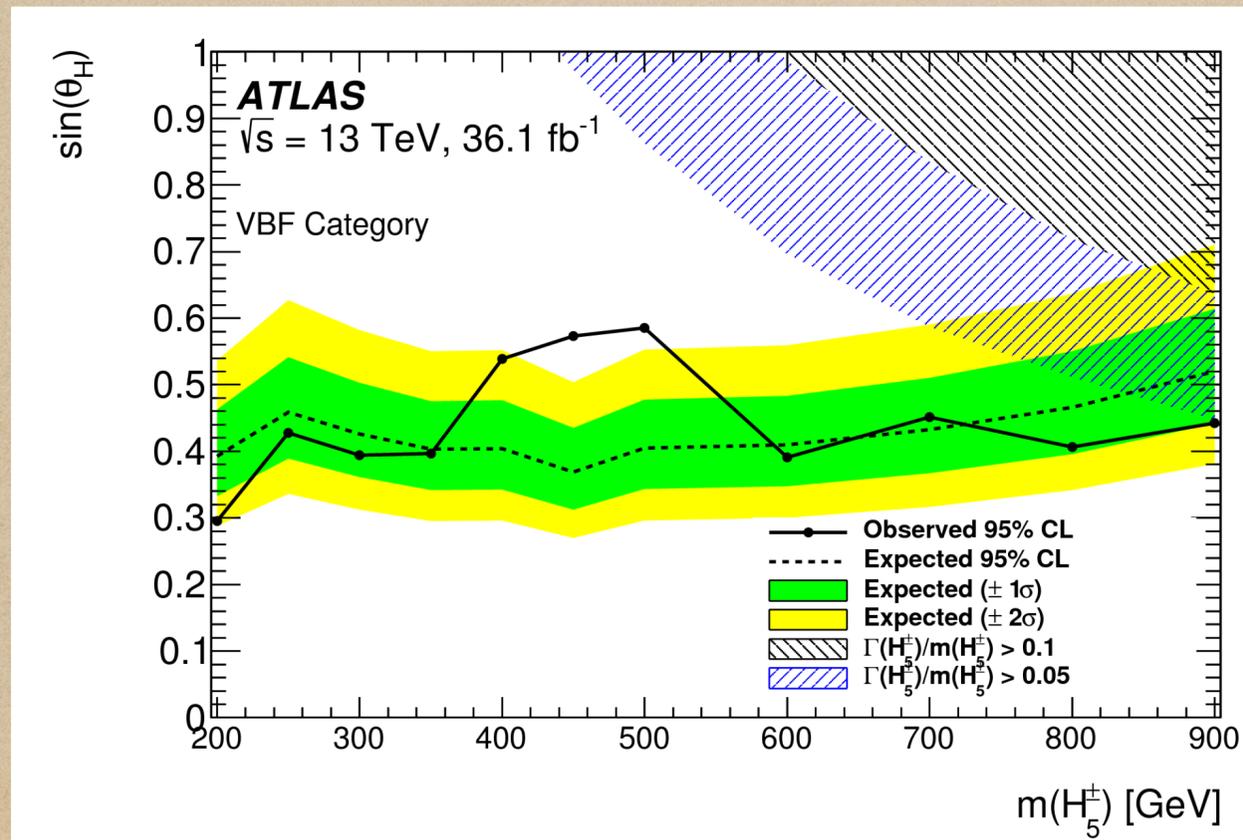
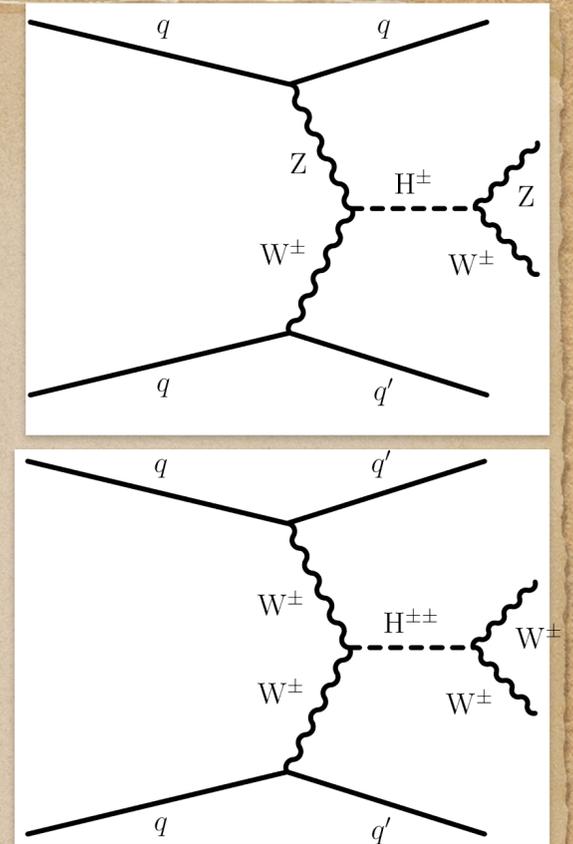
- Search for pair production of H^{±±}, H^{±±} with H[±], or single one from VBF process
- Various models predict it, interpretation: LRS, type II seesaw model, Georgi-Machacek model



H^\pm and $H^{\pm\pm}$ in GM model

- ◆ Georgi-Machacek model
- ◆ Constraints on s_H , where s_H^2 is a fraction of m_W^2 and m_Z^2 generated by the triplet vev's at the tree level

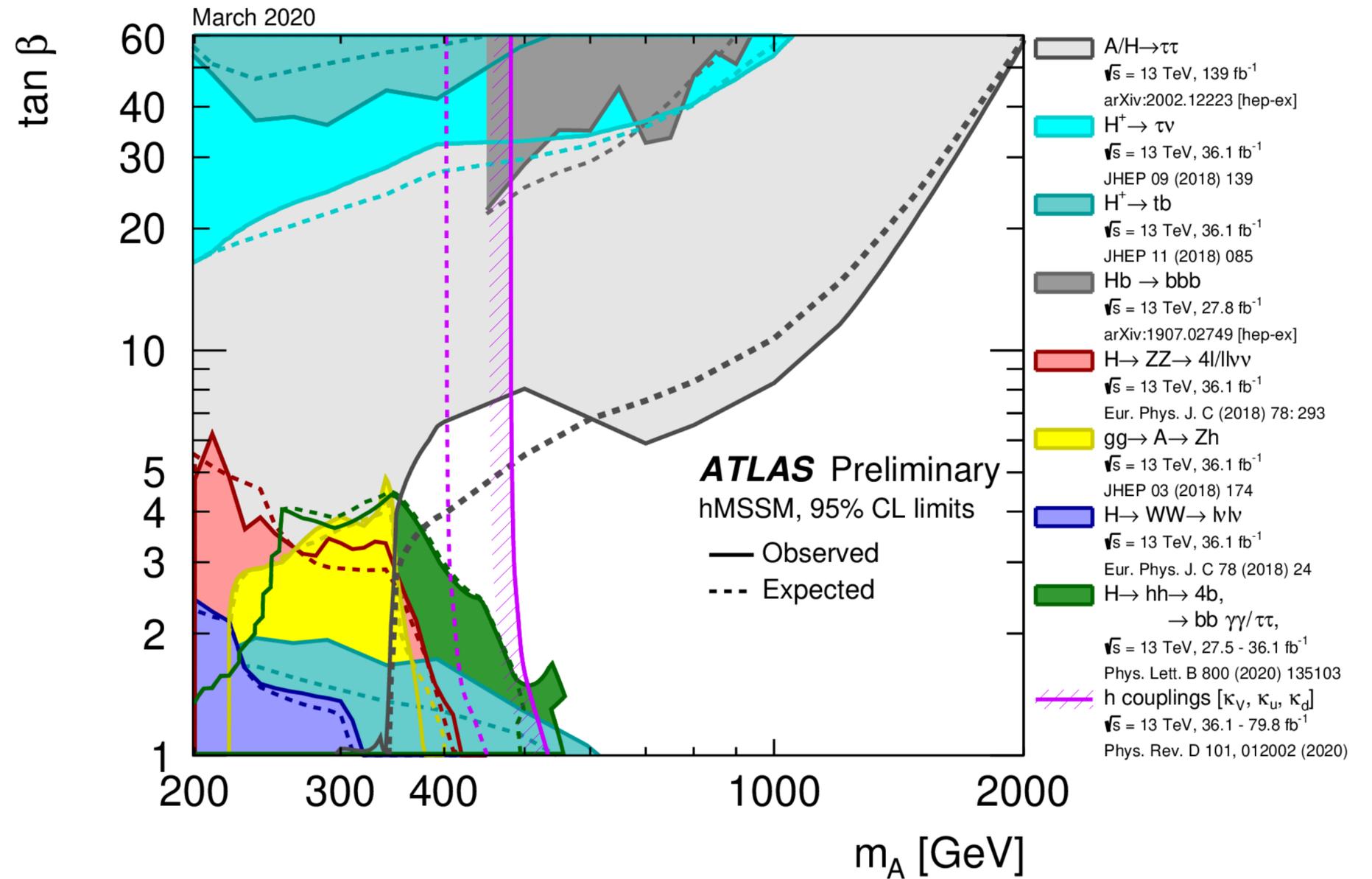
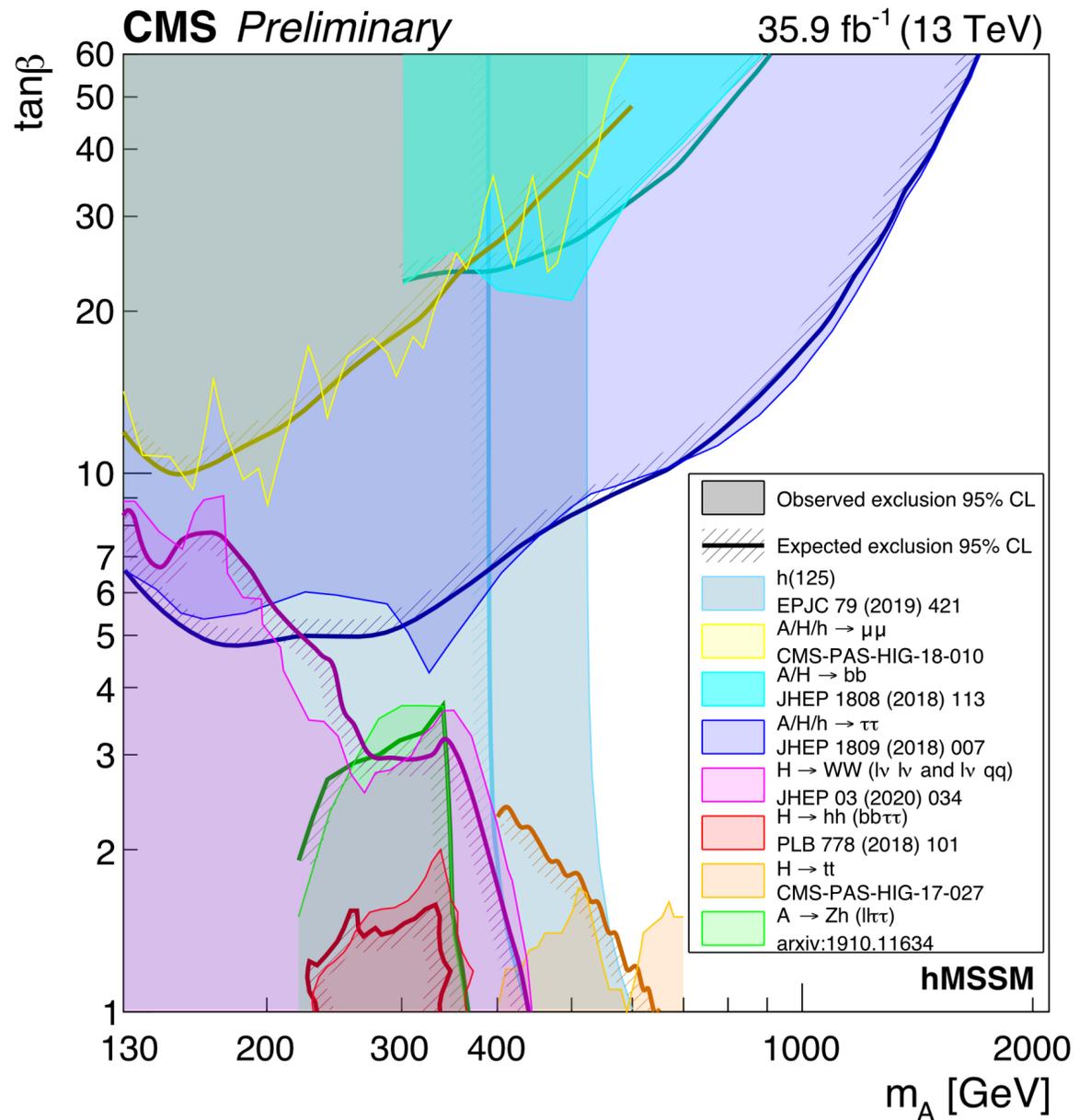
HEPdata - FD, Lim



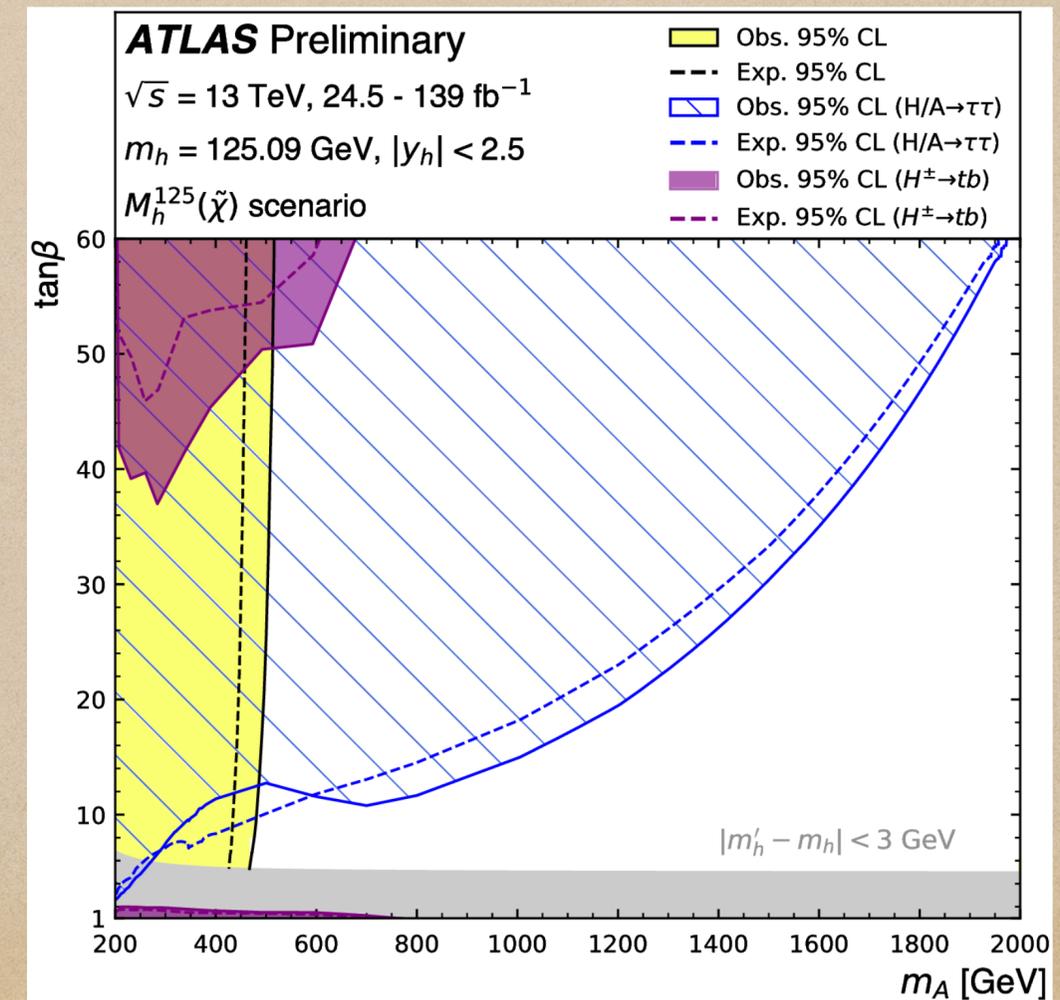
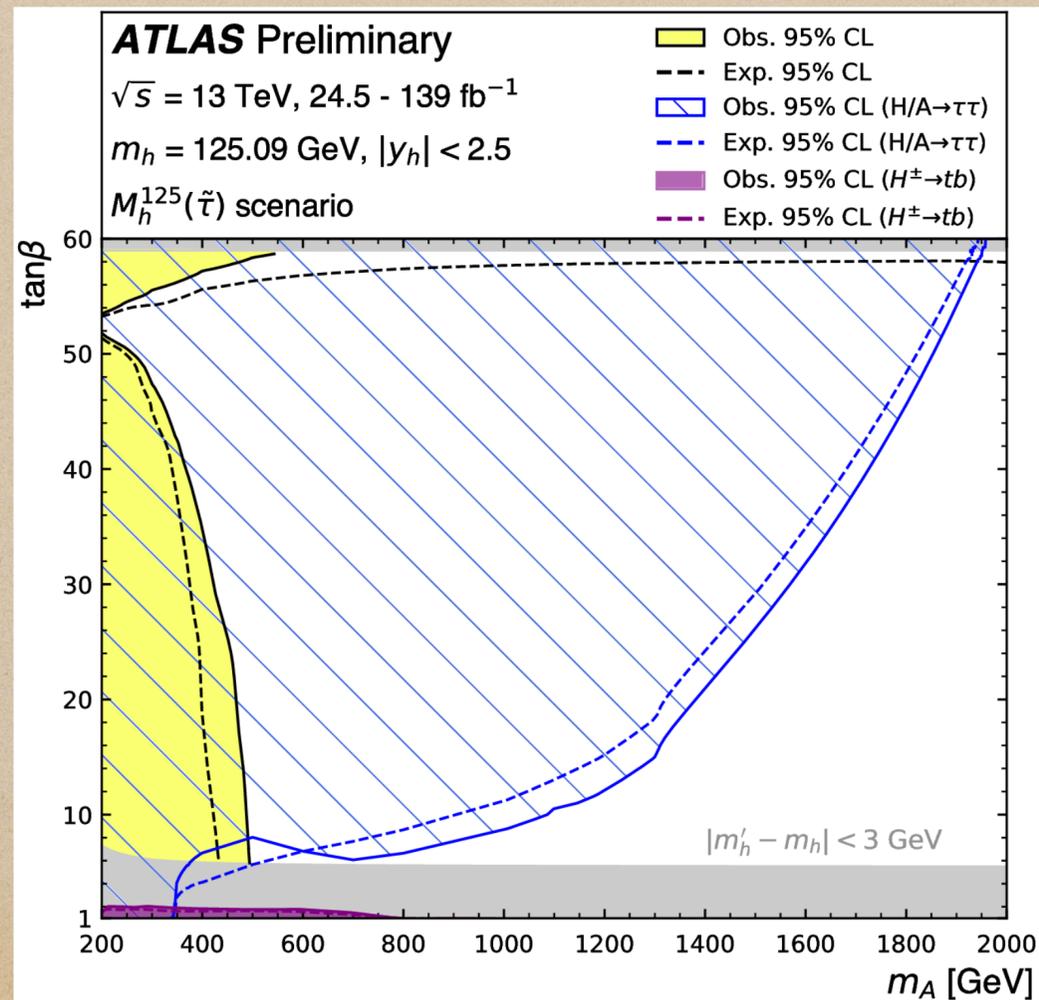
Combination



◆ New results are not yet included



- ◆ Combined measurement of the SM-like Higgs boson interpreted in MSSM
 - ◆ Assumption is that observed Higgs boson is the light CP-even Higgs boson from MSSM
- ◆ Compared with the limits from $H/A \rightarrow \tau\tau$ and $H^\pm \rightarrow tb$

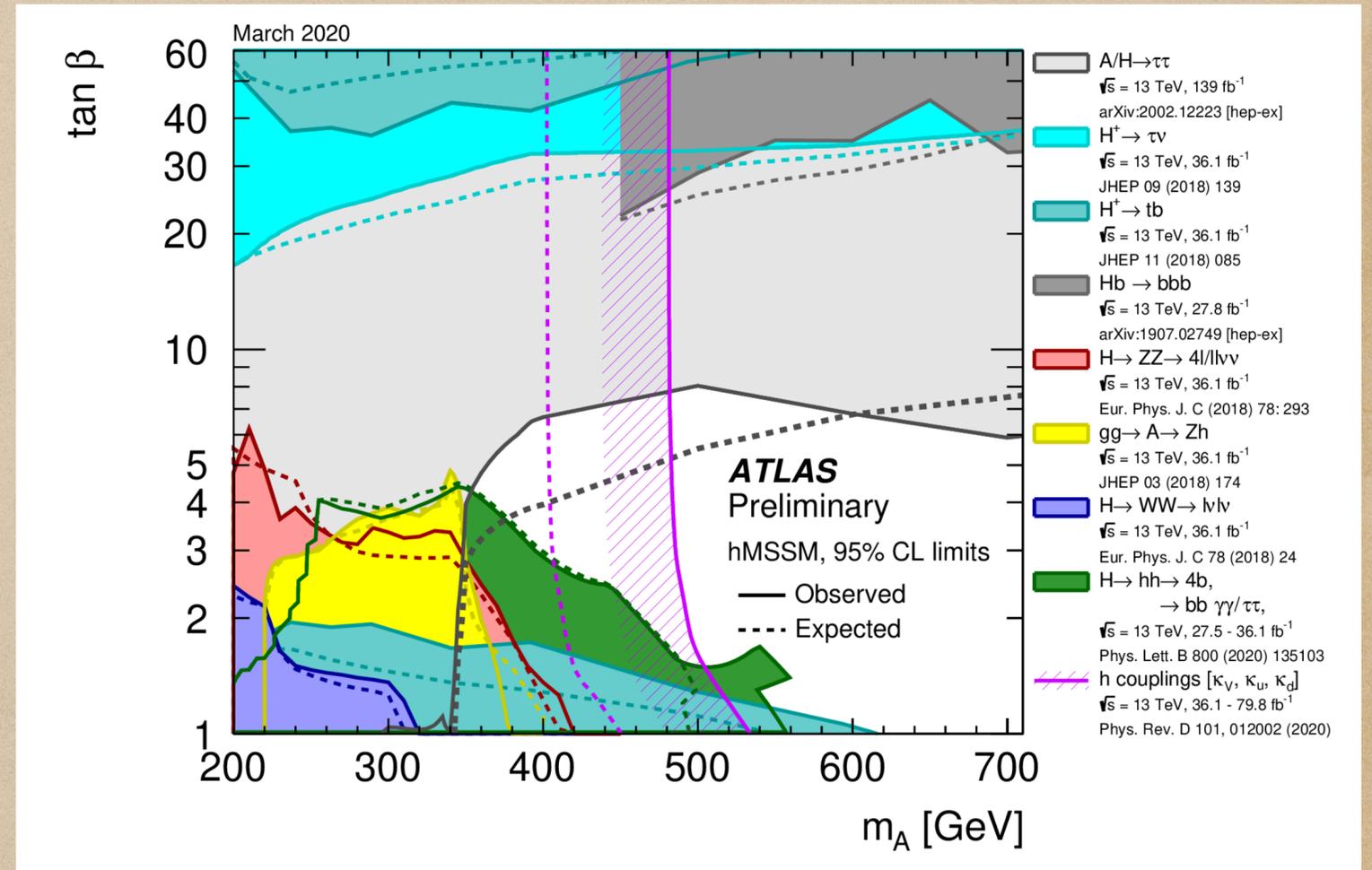


Discussion about systematics

- ◆ In $H/A \rightarrow \tau\tau$ ATLAS and CMS have different approach when theoretical uncertainties on the signal are concerned
 - ◆ ATLAS does not include them, CMS does
- ◆ When HiggsBounds group tried to combine public limits, they could reproduce the ATLAS 139 fb^{-1} result, but not the CMS one at 36 fb^{-1}
- ◆ Difference due to uncertainty on the signal model: was included in the CMS result
 - ◆ HiggsBounds could reproduce it by shifting their limit down by $\sim 1\sigma$
- ◆ Introduction of the theory uncertainty only affects model dependent limits, but effect is small
 - ◆ Model-independent limits on $XS \cdot BR$ is not affected
- ◆ Plots in HEPData is being updated

Summary

- ◆ Plenty of the new results
- ◆ Most interpreted in a model independent way, but also some specific models are investigated
- ◆ Our data is appearing on HEPdata
 - ◆ Feedback is very useful

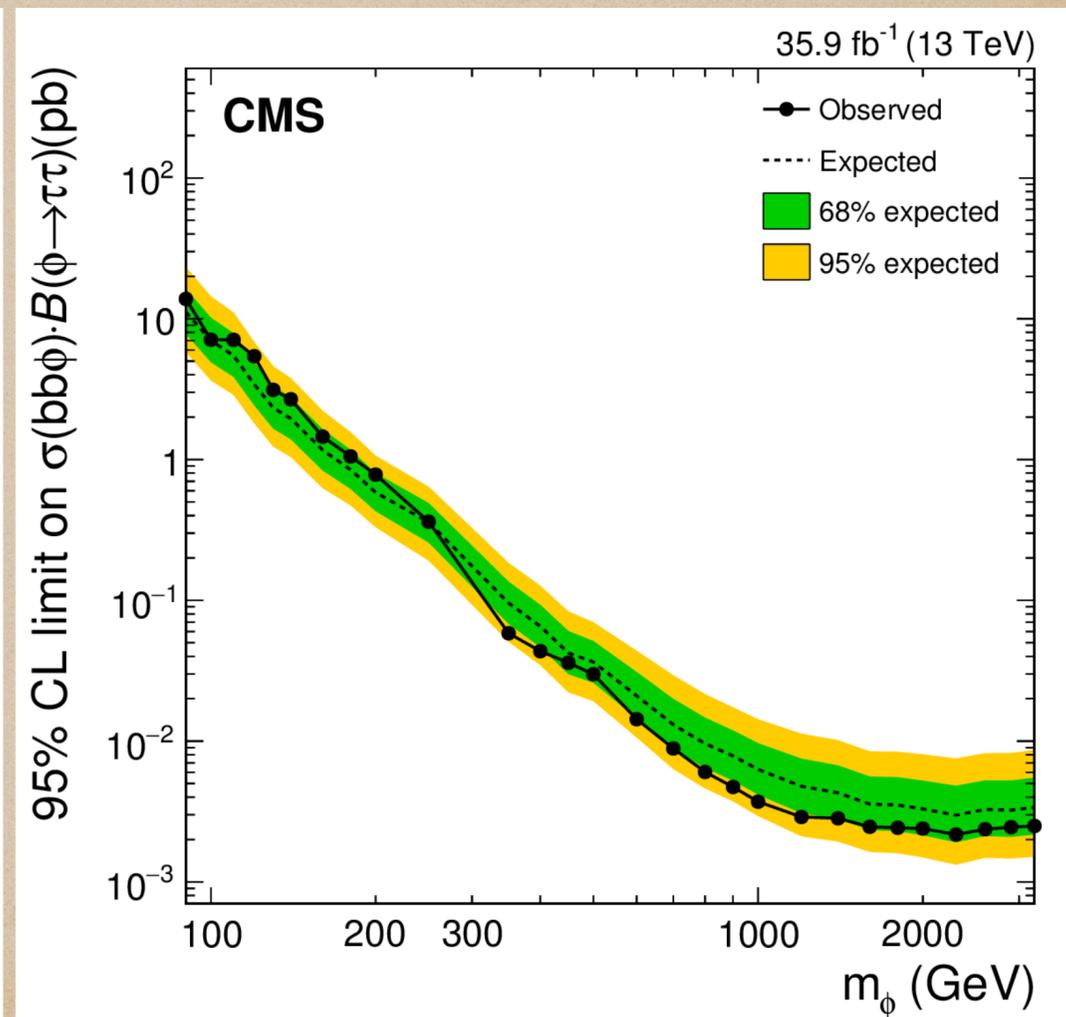
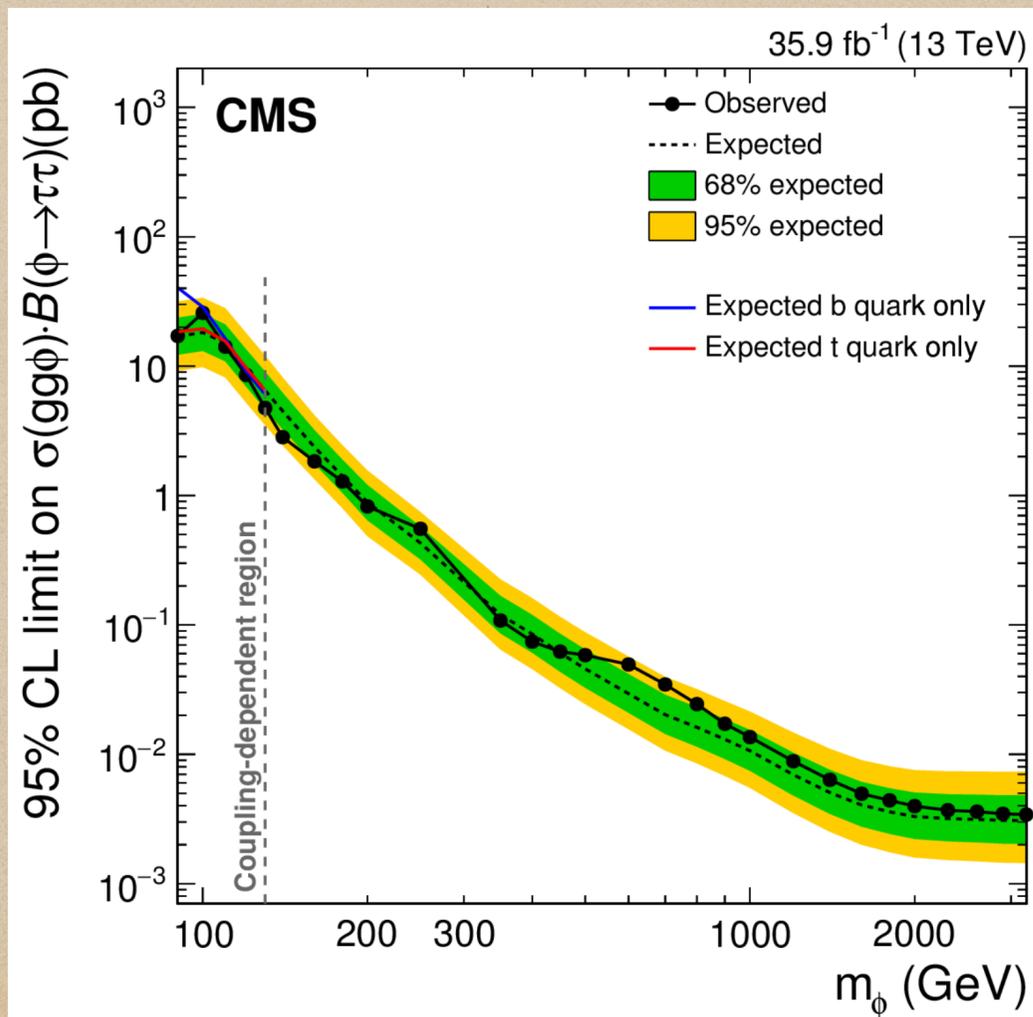
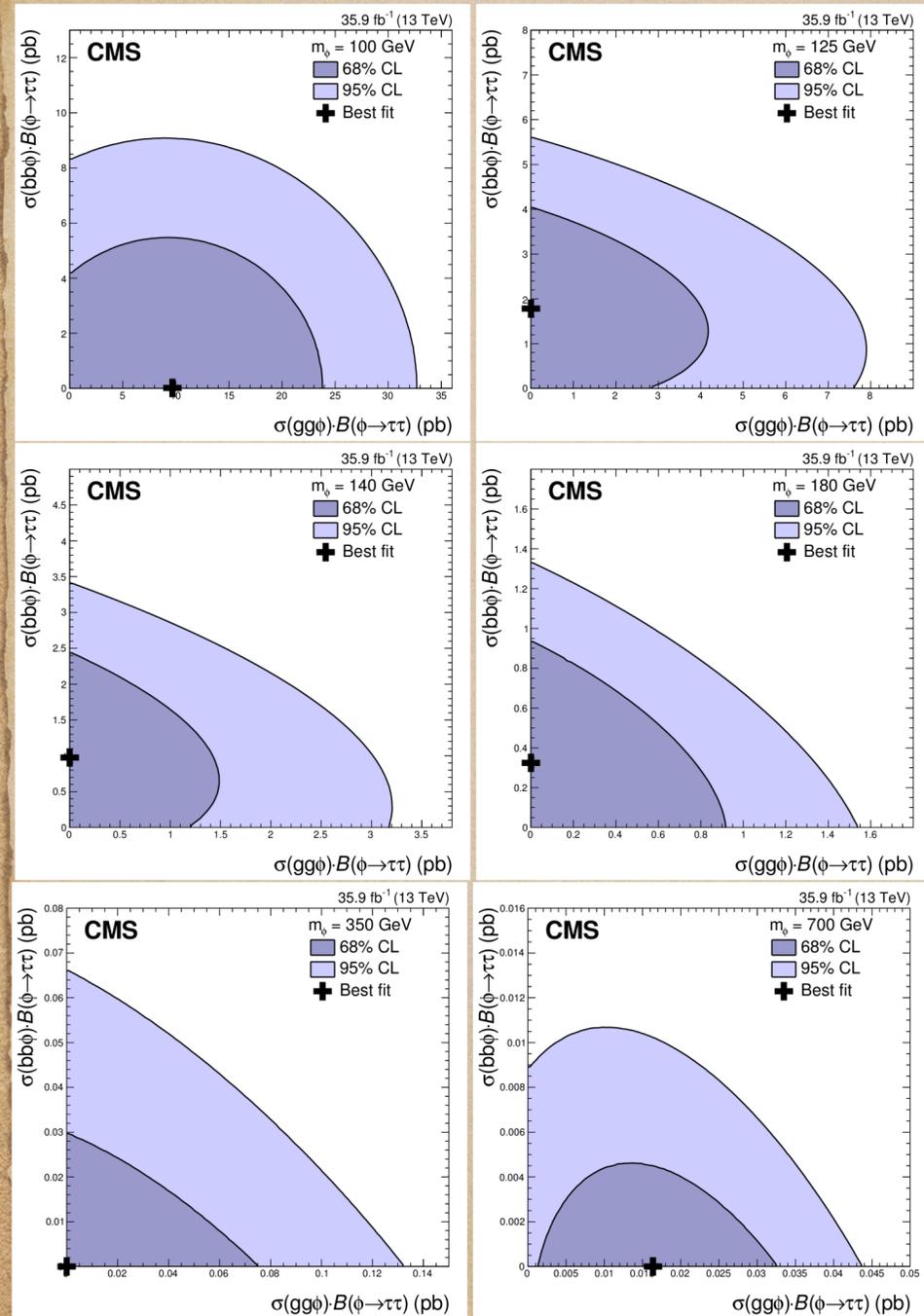
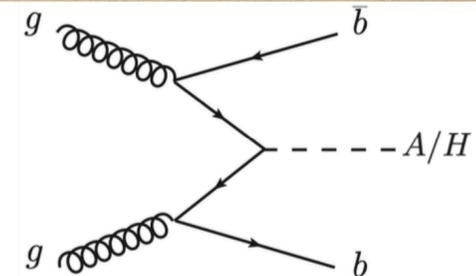
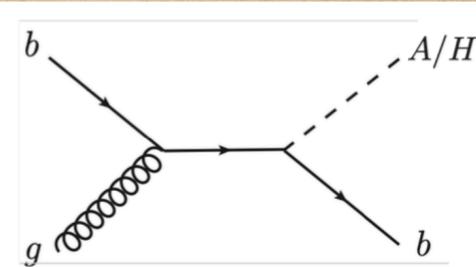
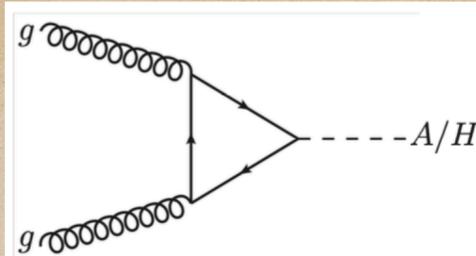




УНИВЕРЗИТЕТ У БЕОГРАДУ
ИНСТИТУТ ЗА ФИЗИКУ | БЕОГРАД
ИНСТИТУТ ОД НАЦИОНАЛНОГ
ЗНАЧАЈА ЗА РЕПУБЛИКУ СРБИЈУ

Backup

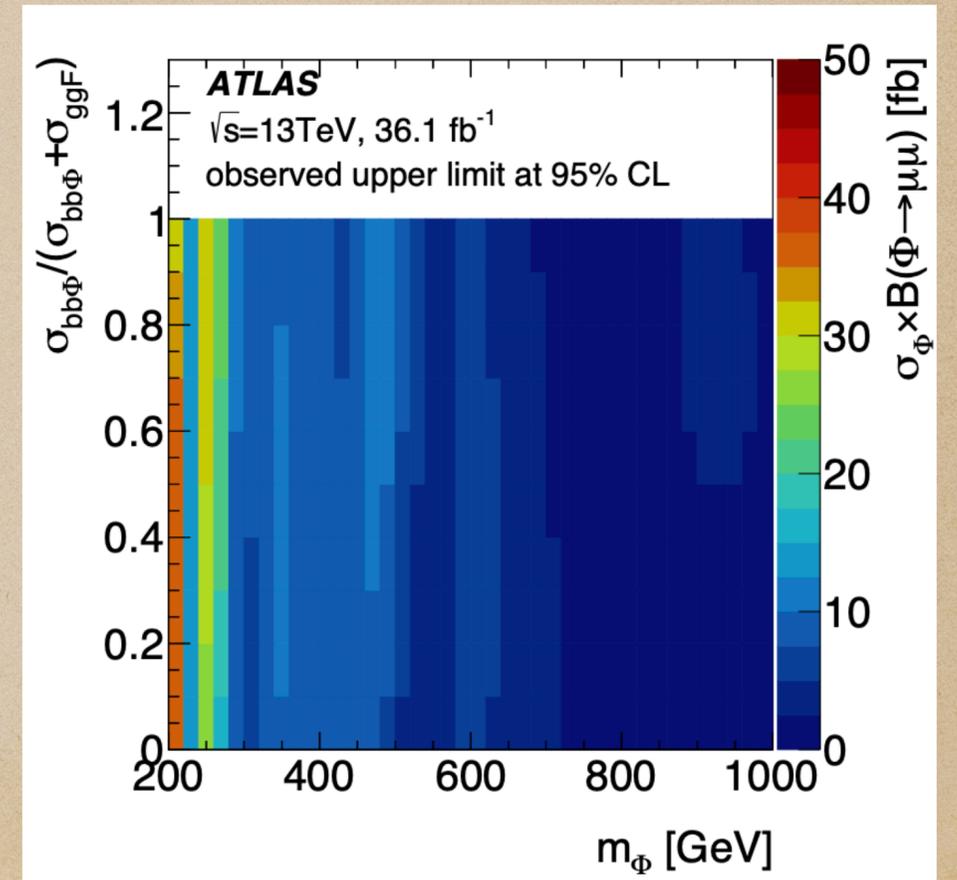
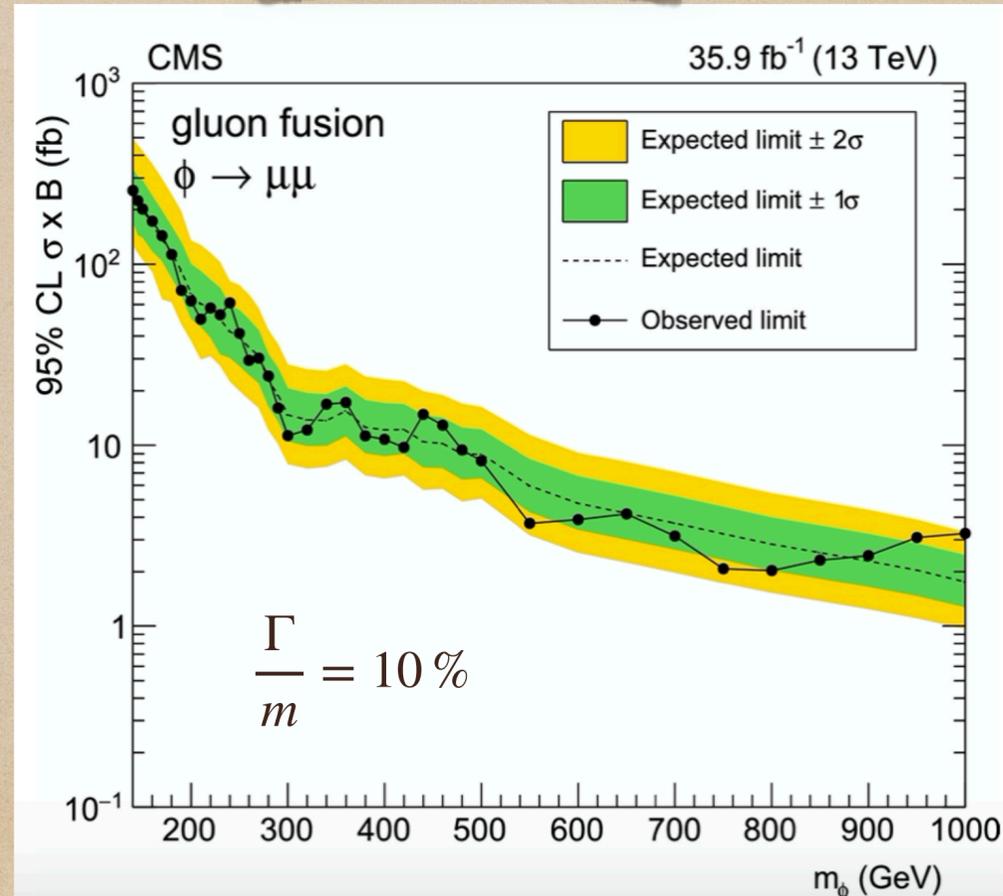
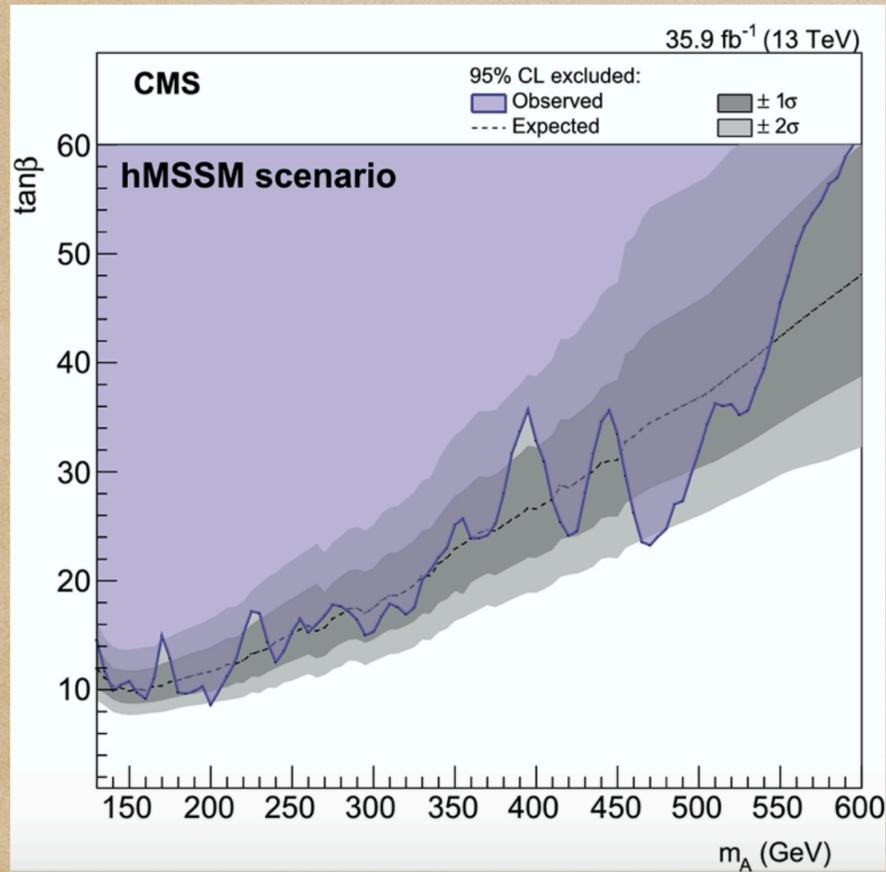
H/A → ττ

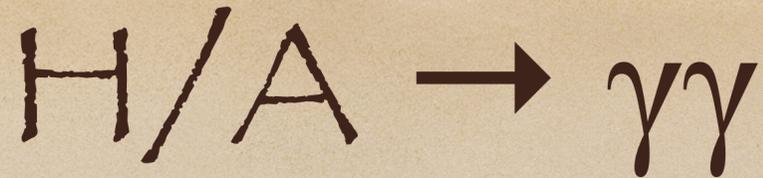


$$H/A \rightarrow \mu\mu$$

- ◆ Gluon fusion and associated with b-quarks
- ◆ Interpreted in MSSM where τ final state dominates - possible models?

Model independent



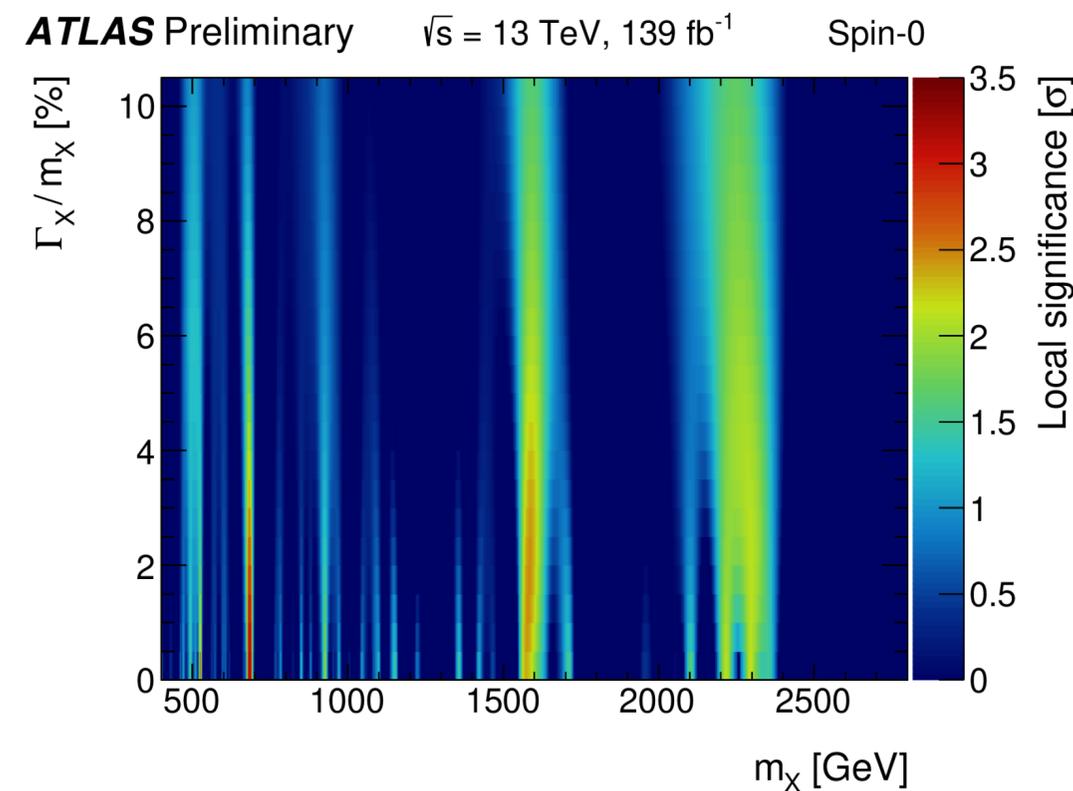
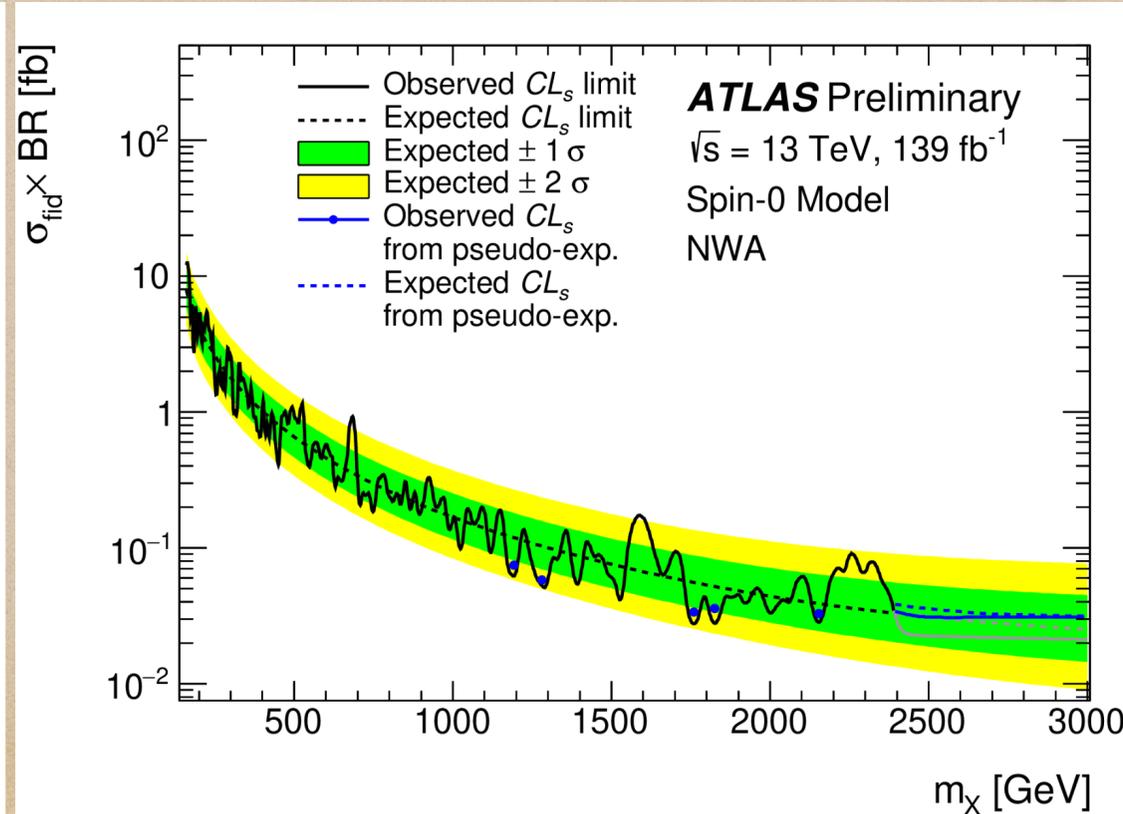
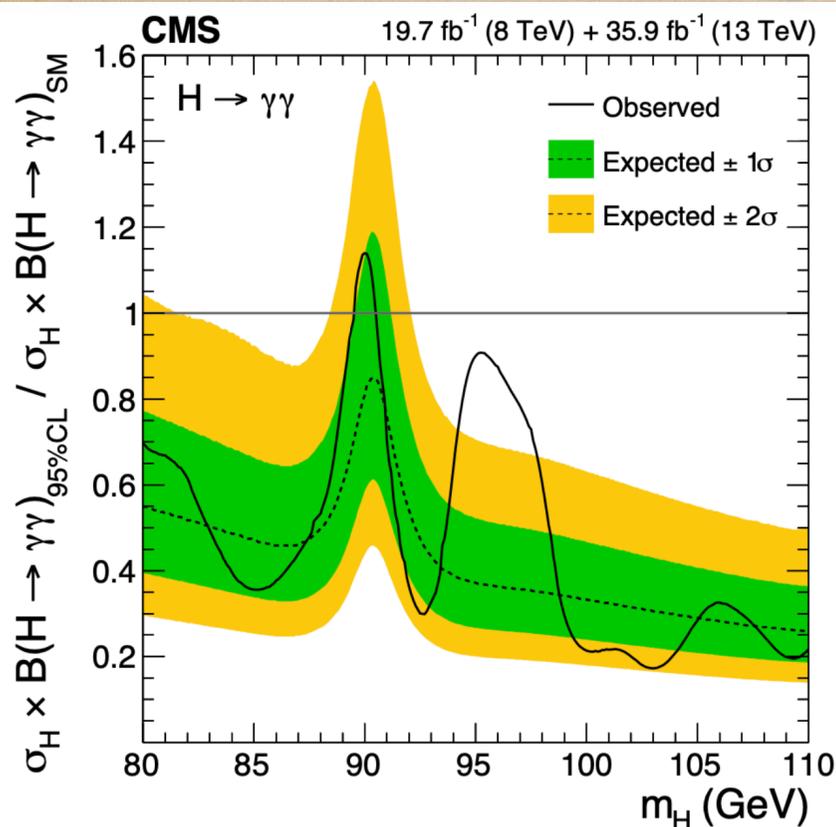


- ◆ Searches for low and high mass resonances
- ◆ Model independent results with minimal assumptions

Misidentified electrons from $Z \rightarrow ee$ are causing signal like events in low mass searches

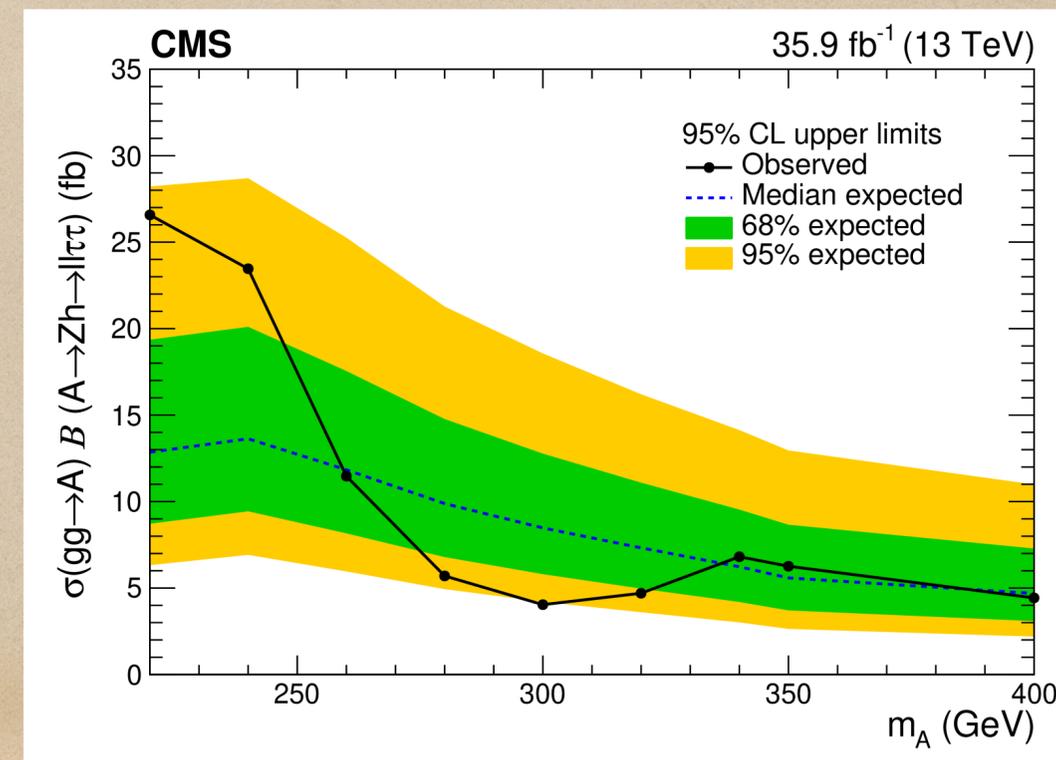
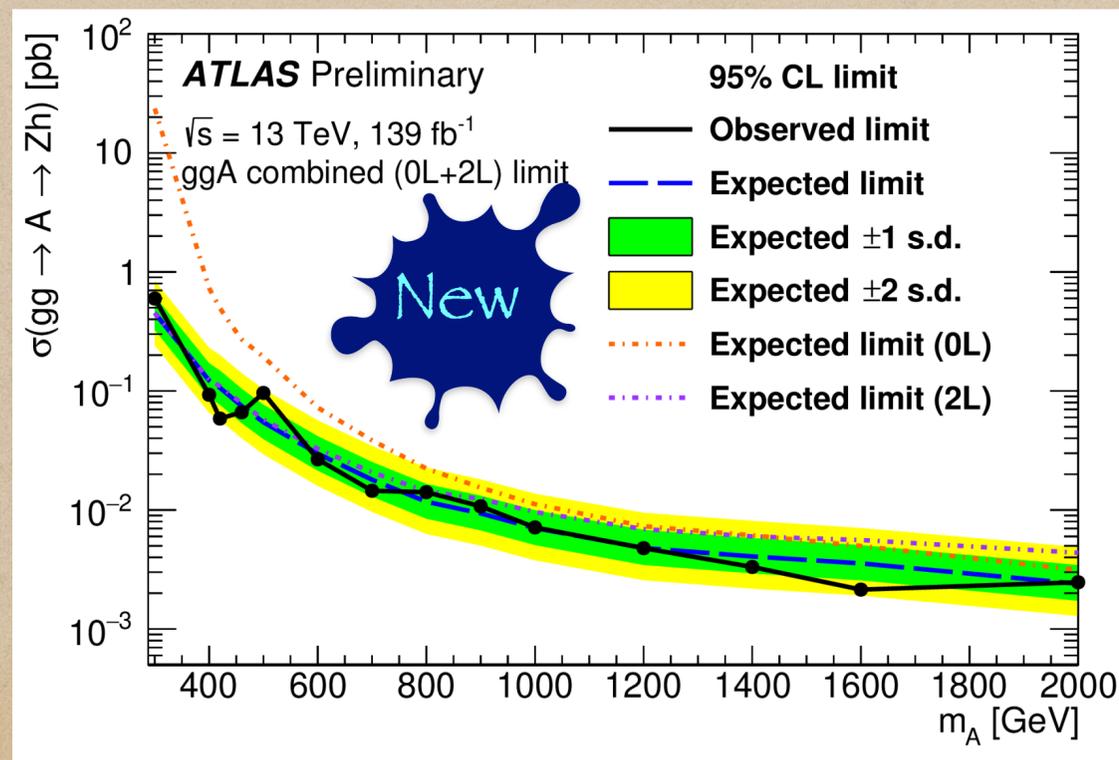
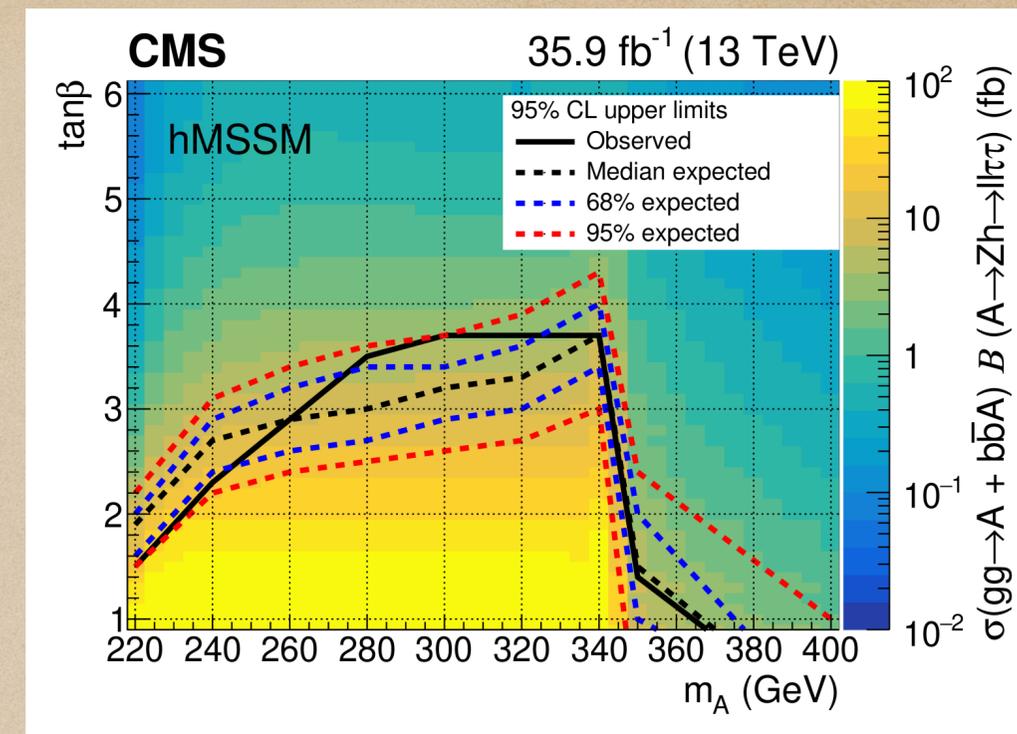
Most significant excess at $m=684$ with local (global) significance of 3.29 (1.30) s.d.

Compatibility with b-only hypothesis



$$A \rightarrow Zh_{SM}$$

- ◆ Gluon fusion production, but also b-associated (CMS), with $h_{SM} \rightarrow bb$ (ATLAS) or $h_{SM} \rightarrow \tau\tau$ (CMS)
- ◆ Besides model independent interpretation, results are also interpreted in MSSM



$A \rightarrow ZH$ and $H \rightarrow ZA$

- Signal extraction accounts for energy resolution of the final-state objects
- Parameter $\rho = i$ contains roughly the fraction of signal events expected within i standard deviations in a 2D distribution.

