Extended Higgs Sector Searches ATLAS+CMS

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Experimental Challenges for LHC Run-II

KITP, April 26, 2016

Introduction

- In the MSSM there are two Higgs doublets
  - Results in 5 physical states:
    - Two CP-even neutral bosons: h,H
    - One CP-odd neutral bosons: A
    - Two charged Higgs bosons: $H^{\pm}$
- At tree-level Higgs sector specified by m_Z, m_A and tanβ, but radiative corrections can be large
  - Most important corrections from top mass, SUSY breaking scale and stop mixing
  - Use different scenarios for other SUSY parameters when making interpretations of observed limits on new Higgs bosons
- MSSM Higgs sector is one example of generic 2HDM
  - MSSM is a so-called type-II 2HDM
  - Most searches present results in multiple 2HDM scenarios, but will focus on MSSM scenarios today

(MSSM) Neutral Higgs Searches

	ATLAS		CMS	
	8 TeV	**13 TeV**	**8 TeV**	**13 TeV**
$A/H \to \tau\tau$	1409.6064	CONF-2015-061	HIG-14-029	
$A/H \to \mu\mu$			1508.01437	
$A/H \to b\bar{b}$			1506.08329	
$A \to Zh$	1502.04478	CONF-2016-015	1504.04710, 1510.01181	
$H \to ZA$			1603.02991	HIG-16-020
$H \to hh$	1506.00285, 1509.04670, 1406.5053	CONF-2016-017, CONF-2016-004	1503.04114, 1510.01181, 1603.06896, HIG-15-013	HIG-16-002, HIG-16-011, HIG-16-013
$H \to ZZ$	1507.05930	CONF-2015-068, CONF-2015-071, CONF-2016-010	1504.00936	HIG-16-001
$H \to WW$	1509.00389	CONF-2015-075	1504.00936	
$X \to \gamma\gamma$	1407.6583	CONF-2016-018	1506.02301,	EXO-16-018
$X \to Z\gamma$		CONF-2016-010	HIG-16-014	EXO-16-019

MSSM Charged Higgs Searches

	ATLAS		CMS	
	8 TeV	**13 TeV**	**8 TeV**	**13 TeV**
$H^+ \to \tau\nu$	1412.6663	1603.09203	1508.07774	
$H^+ \to cs$			1510.04252	
$H^+ \to tb$	1512.03704		1508.07774	
$H^+ \to WZ$	1503.04233			

Searches for H^{++} also exists, but not covered today

NMSSM Light Scalar Searches

- NMSSM adds two new singlets to 2HDM
  - Allows 125 GeV Higgs without heavy stop
  - One new singlet could be very light

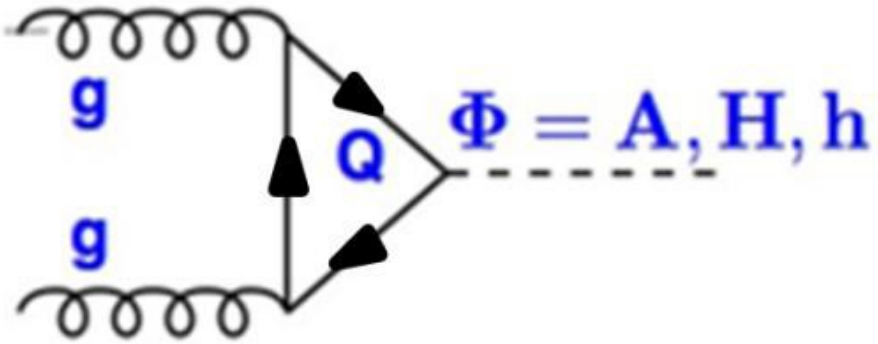
	ATLAS		CMS	
	8 TeV	**13 TeV**	**8 TeV**	**13 TeV**
$h \to aa \to \tau\tau\tau\tau$			1510.06534, HIG-14-022	
$h \to aa \to \mu\mu\tau\tau$	1505.01609		HIG-15-011	
$h \to aa \to \mu\mu\mu\mu$	1505.07645		1506.00424	
$h \to aa \to \mu\mu b\bar{b}$			HIG-14-041	
$h \to aa \to \gamma\gamma\gamma\gamma$	1509.05051			
$a \to b\bar{b}$			HIG-14-030	
$a \to \tau\tau$			HIG-14-033	
Light $h \to \gamma\gamma$			HIG-14-037	

More luminosity needed for Run-2 to compete with Run-1 results

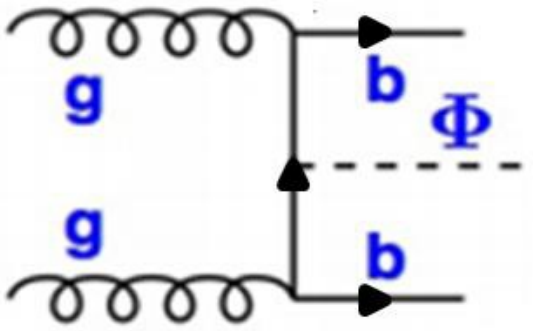
A/H→ττ Searches

- Main search for heavy MSSM Higgs at high tan β
- Split by production mode

Gluon fusion



B-associated production

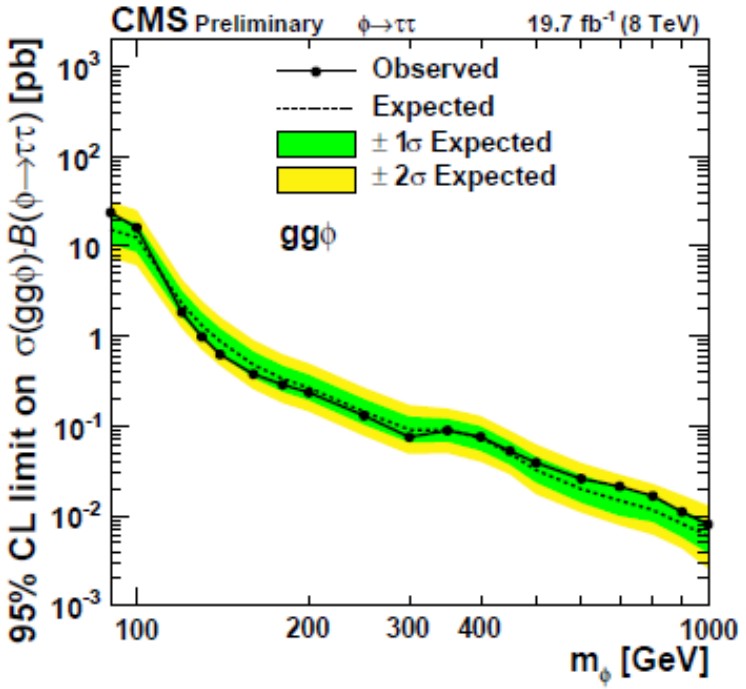


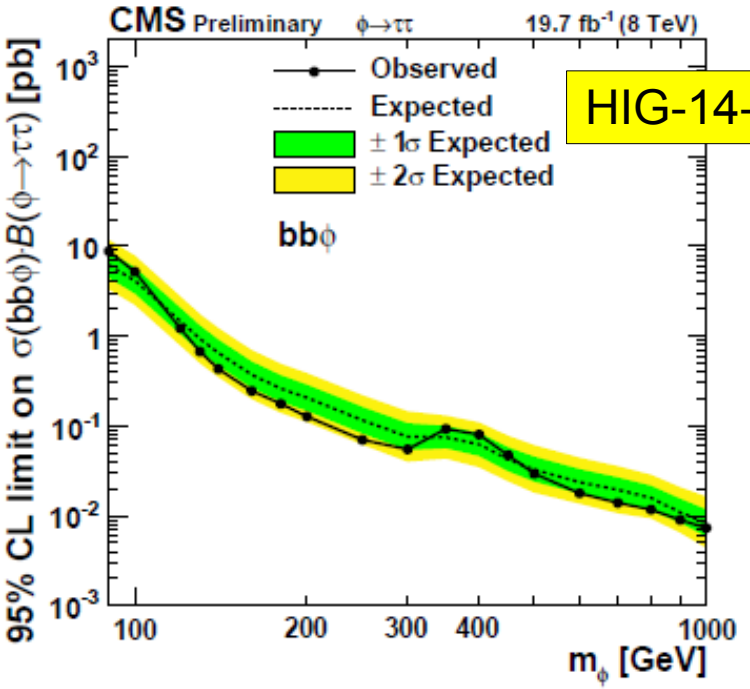
- Further split by τ decay modes
  - $\tau_{lep}\tau_{had}$ best sensitivity at low masses
    - Dominant backgrounds Z→ττ and top (from MC)
  - $\tau_{had}\tau_{had}$ best sensitivity at high masses
    - Multijets dominant background – data-driven (fake taus)
  - $\tau_{lep}\tau_{lep}$ only some combinations

A/H→ττ Searches

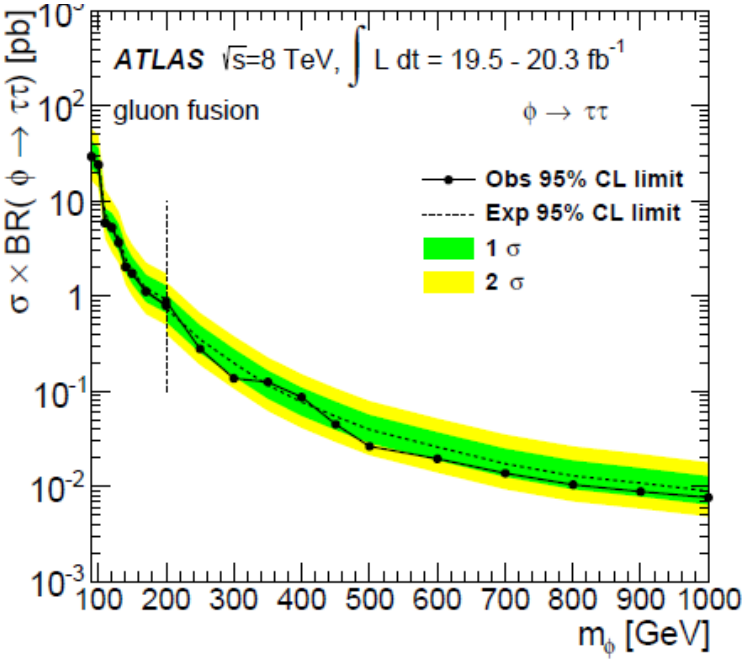
CMS
8 TeV
updated
with
improved
τ_{had} ID
and split
by $p_T(\tau_{had})$

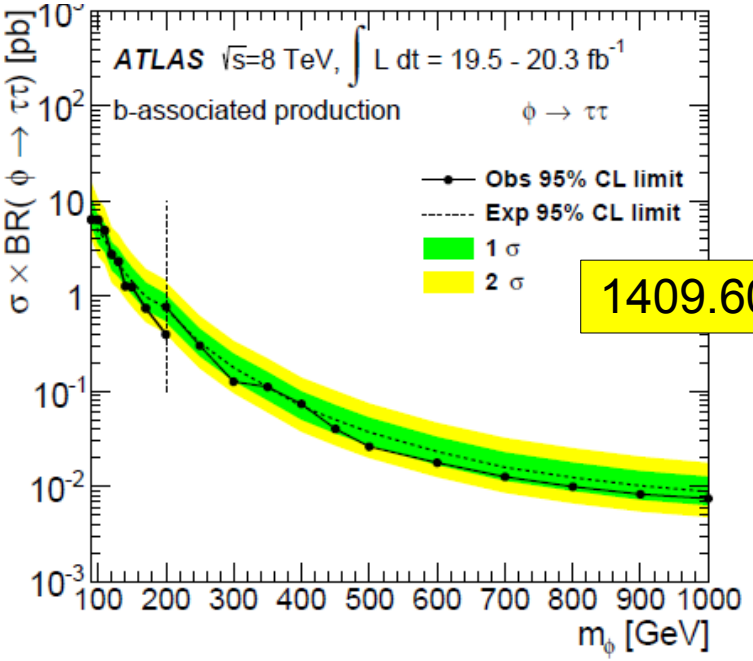
ATLAS
8 TeV





HIG-14-029



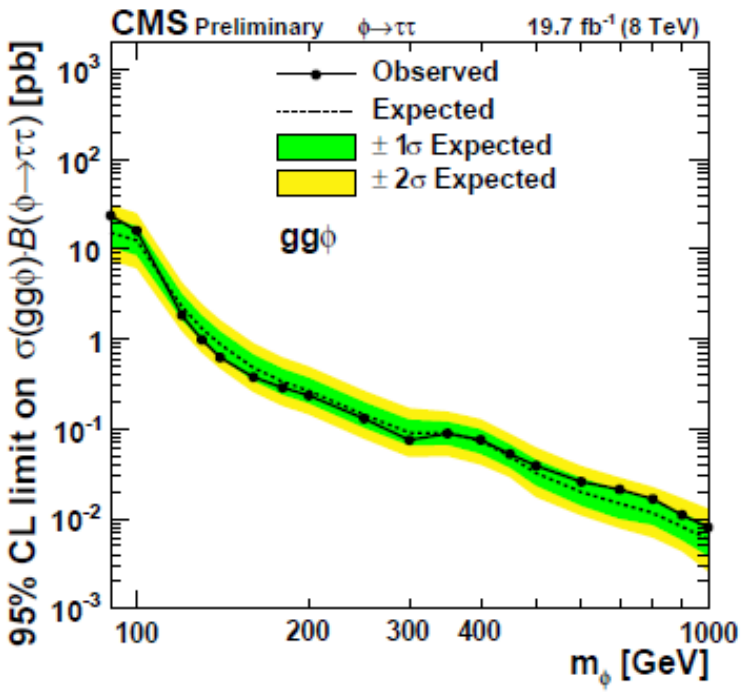


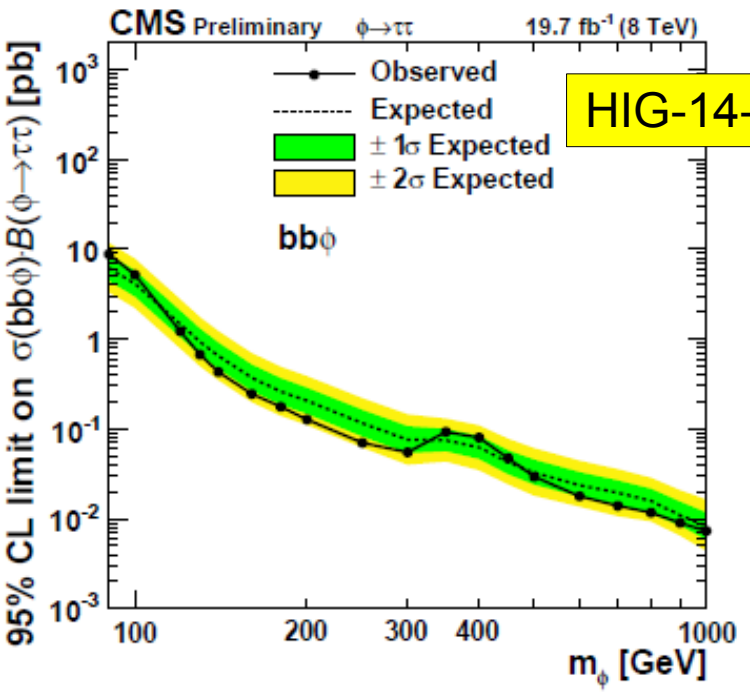
1409.6064

A/H→ττ Searches

CMS
8 TeV
updated
with
improved
τ_{had} ID
and split
by $p_T(\tau_{had})$

Recent
ATLAS
13 TeV
(high-
mass
only)





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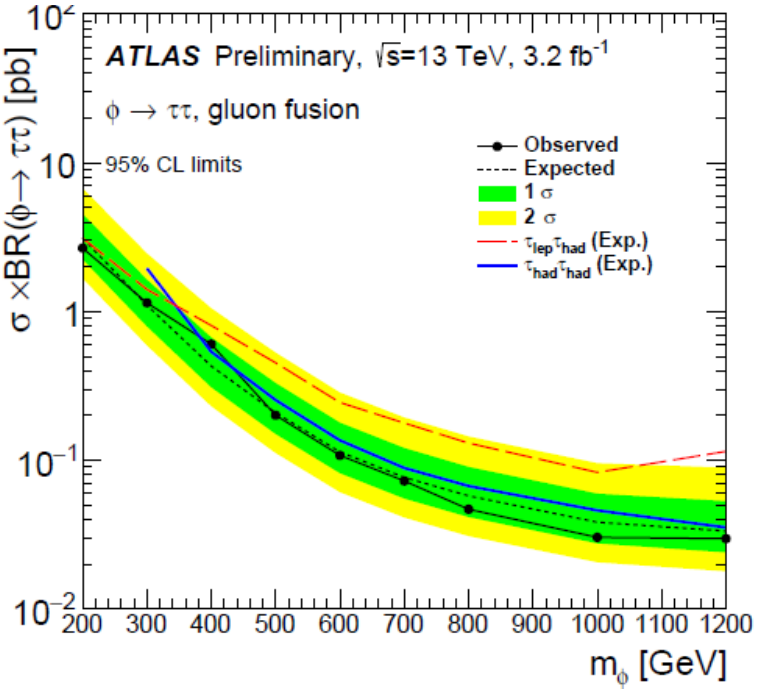
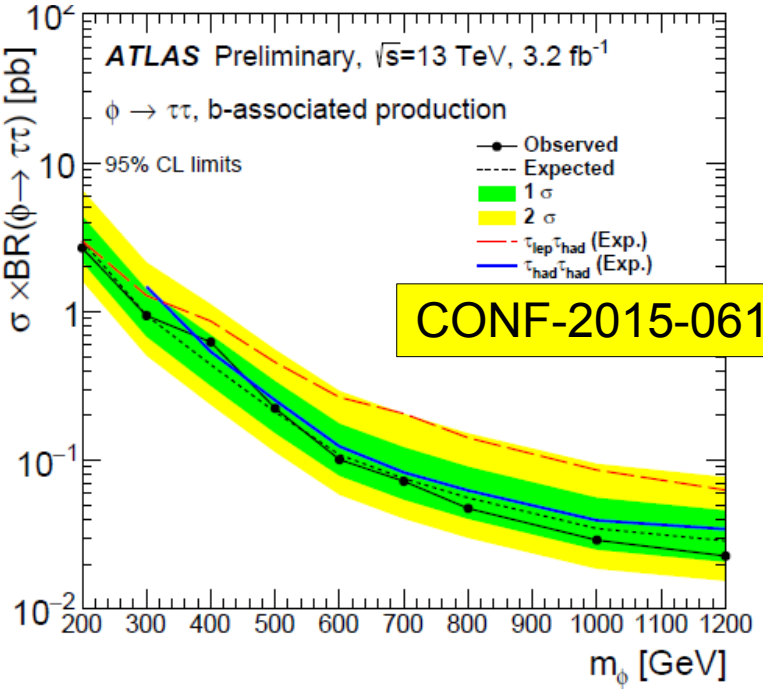
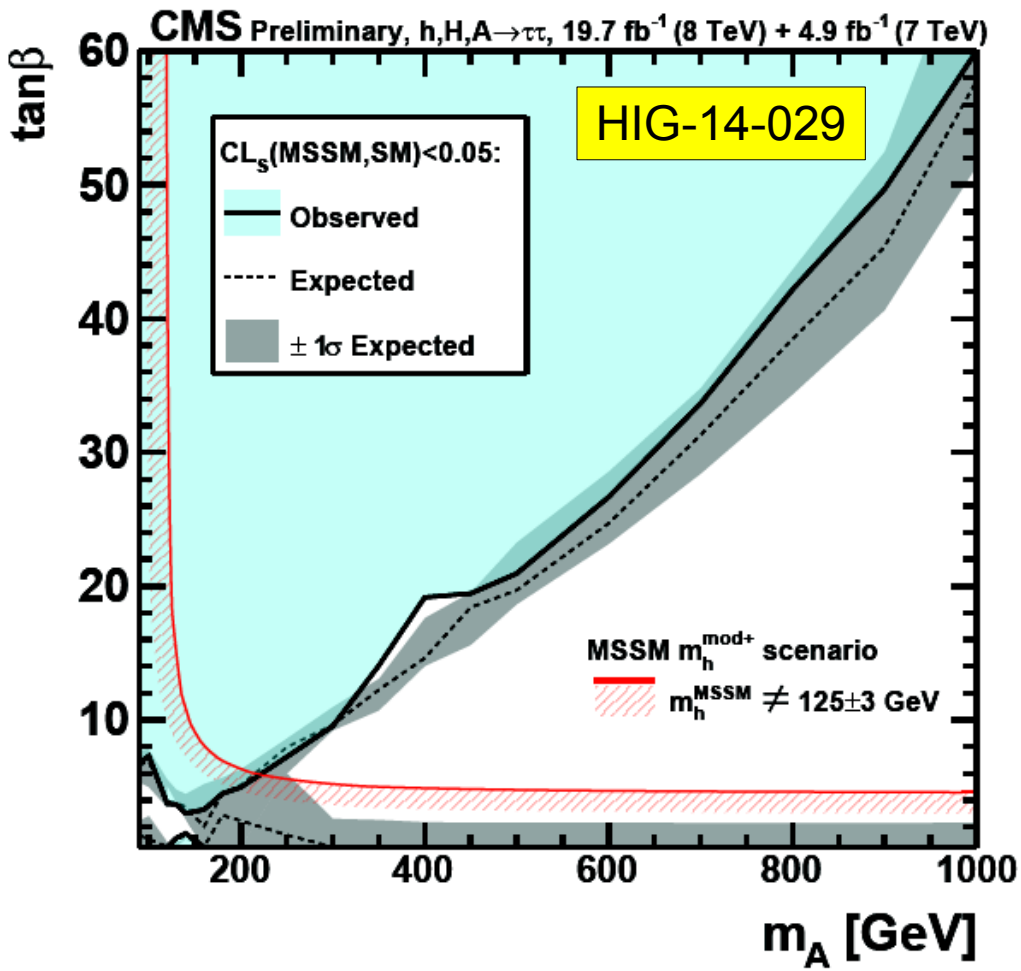


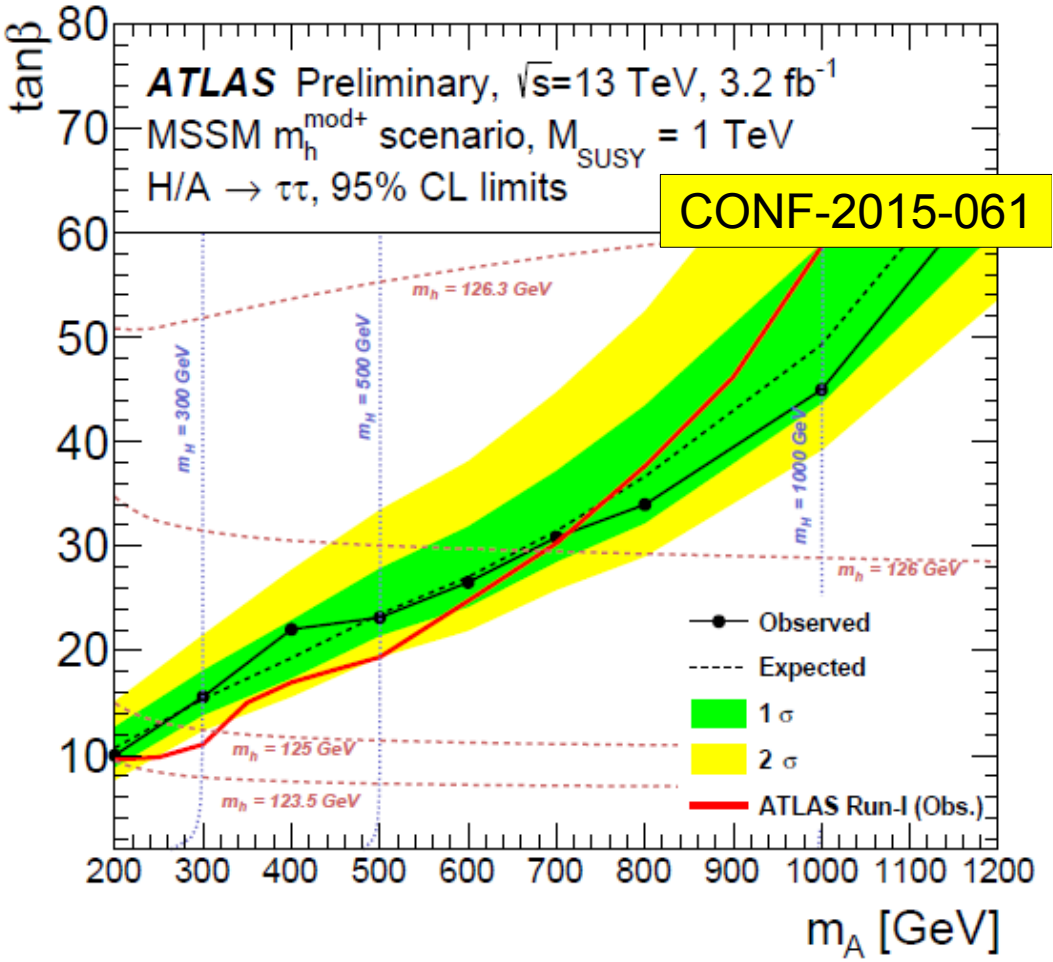


CONF-2015-061

A/H→ττ Searches

Non-observation interpreted as limit in (m_A, tanβ) plane for various MSSM scenarios (m_h^{max}, $m_h^{mod\pm-}$, hMSSM, light stop/stau, tauphobic)

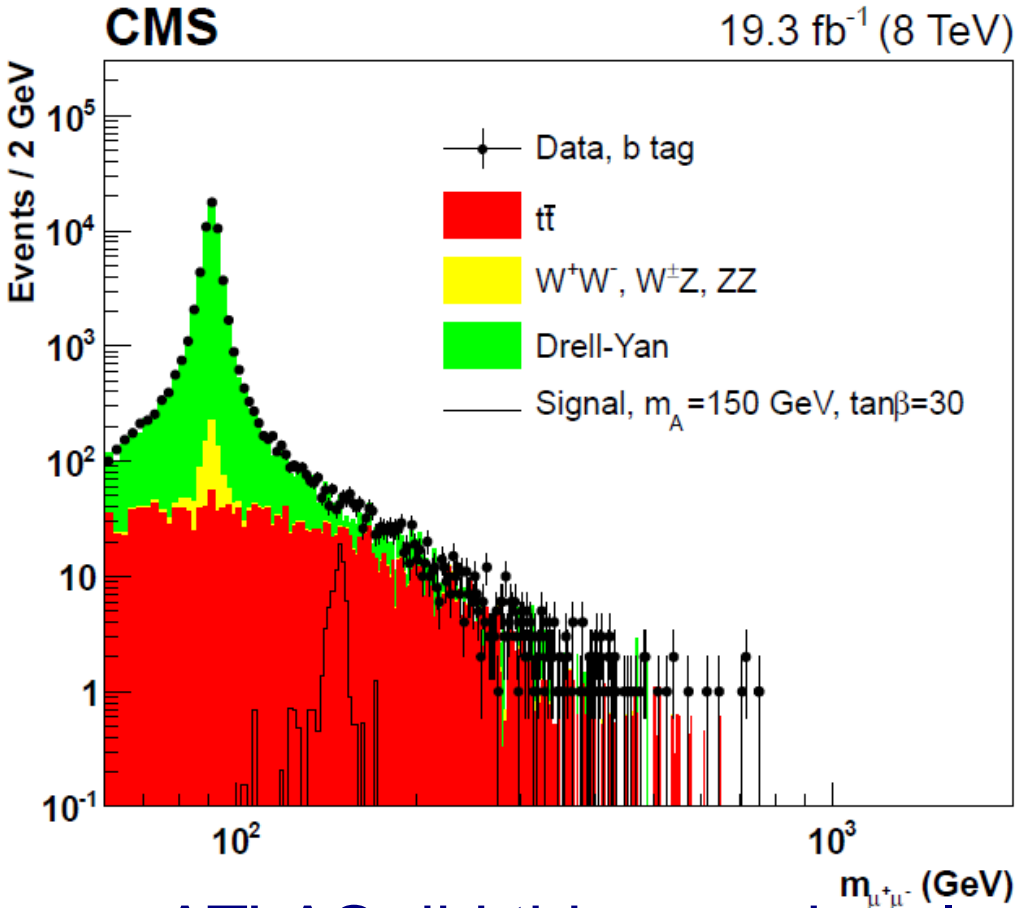


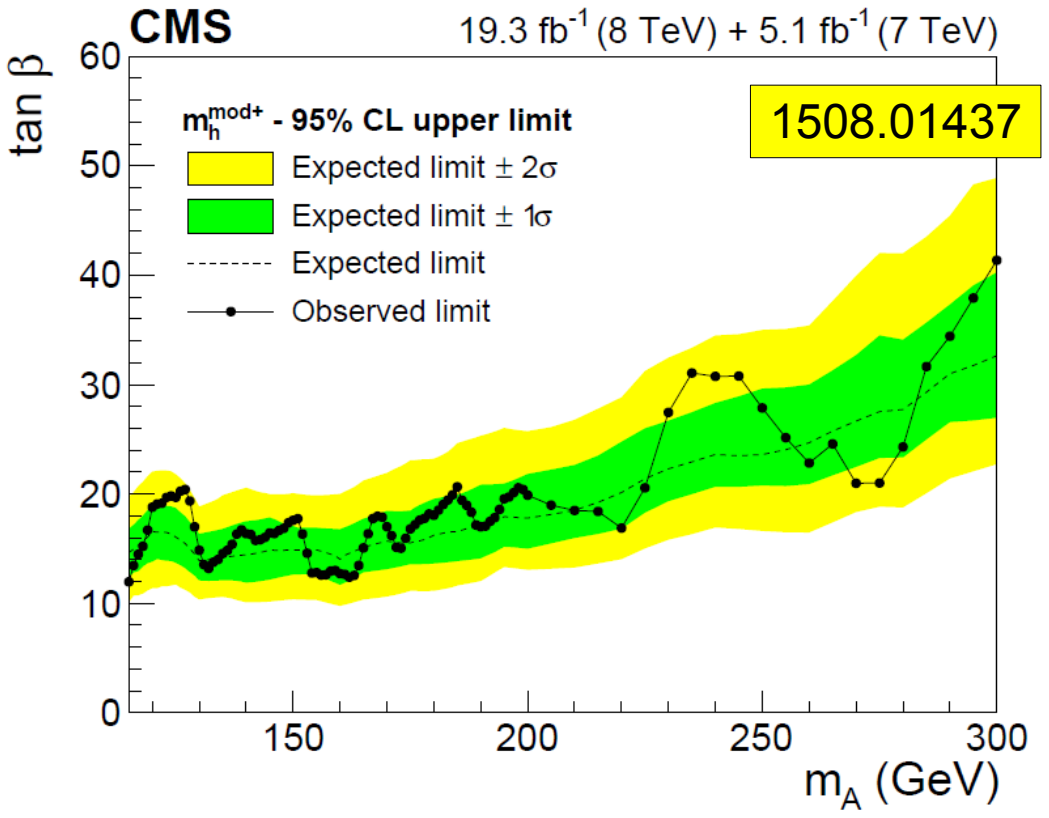


In all scenarios 13 TeV ATLAS result surpasses Run-1 limits for m_A~6-700 GeV

A/H→μμ Search

- Can also search in di-muon channel for high tanβ
  - Expect BF O(10^3) smaller than ττ, but experimentally clean, efficient reconstruction and excellent mass resolution
  - Also split in gluon-fusion and b-associated production

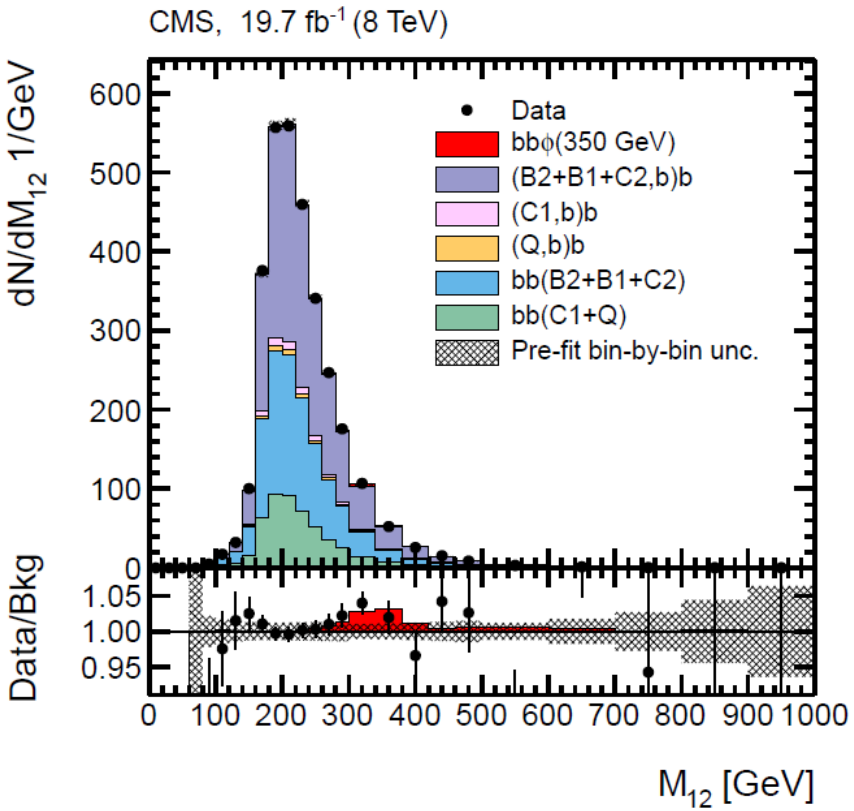


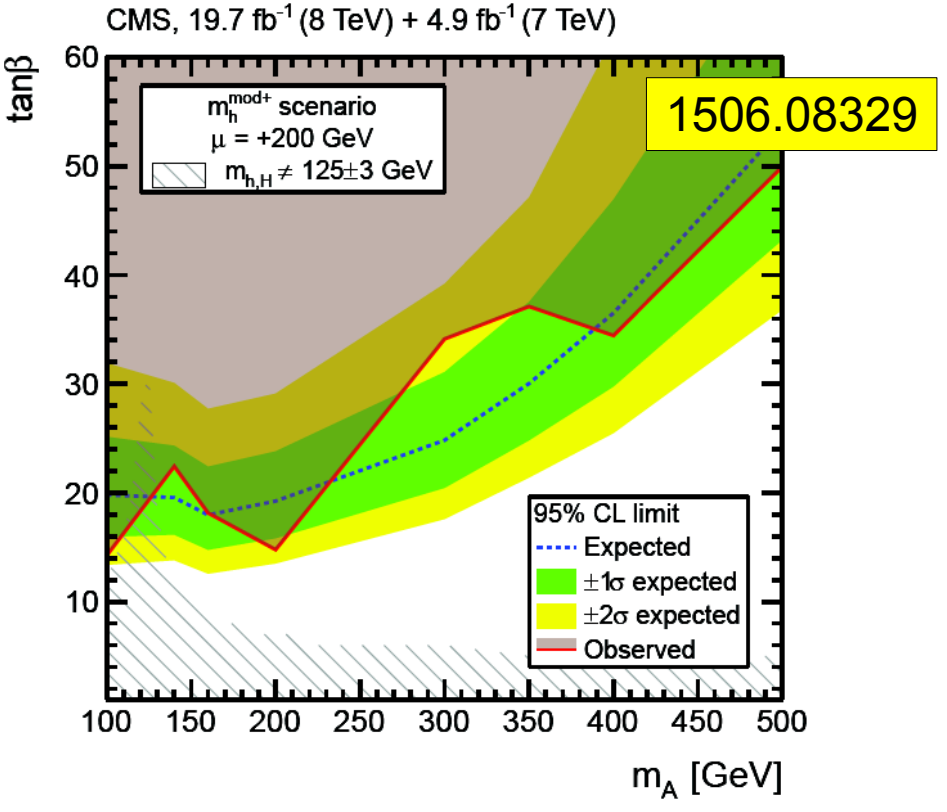


ATLAS did this search only at 7 TeV so far

A/H→bb Search

- For tanβ>1 A/H→bb dominant (BF~90%)
- Difficult channel due to massive multi-jet background
  - CMS uses special di-bjet trigger with $|\eta|<1.74$, $p_{T1,2}>80/70$ GeV
- Only b(b)H production considered (3-bjets required)
  - 2-bjet events used to estimate multijet background
  - Use m_{bb} and event-level b-tagging variable to extract signal





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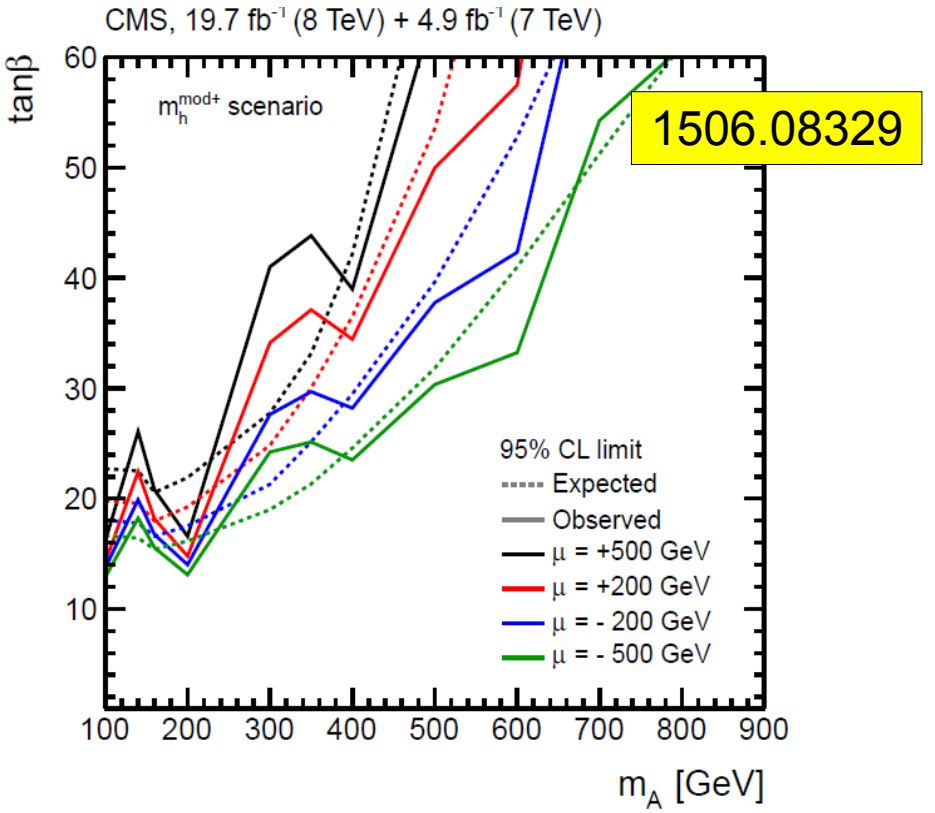
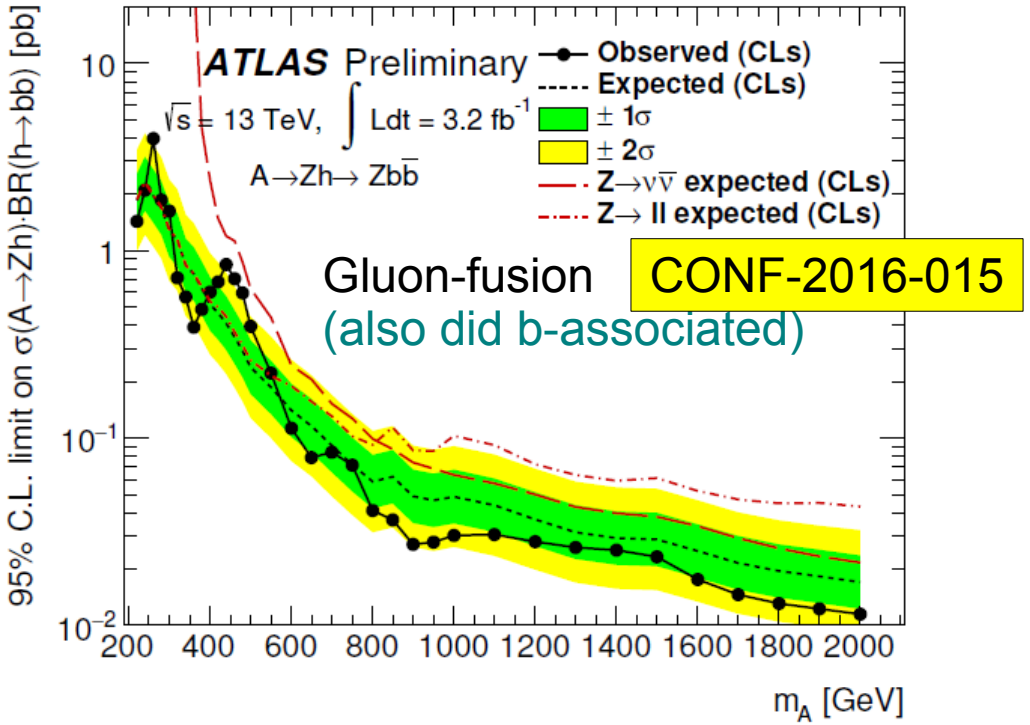
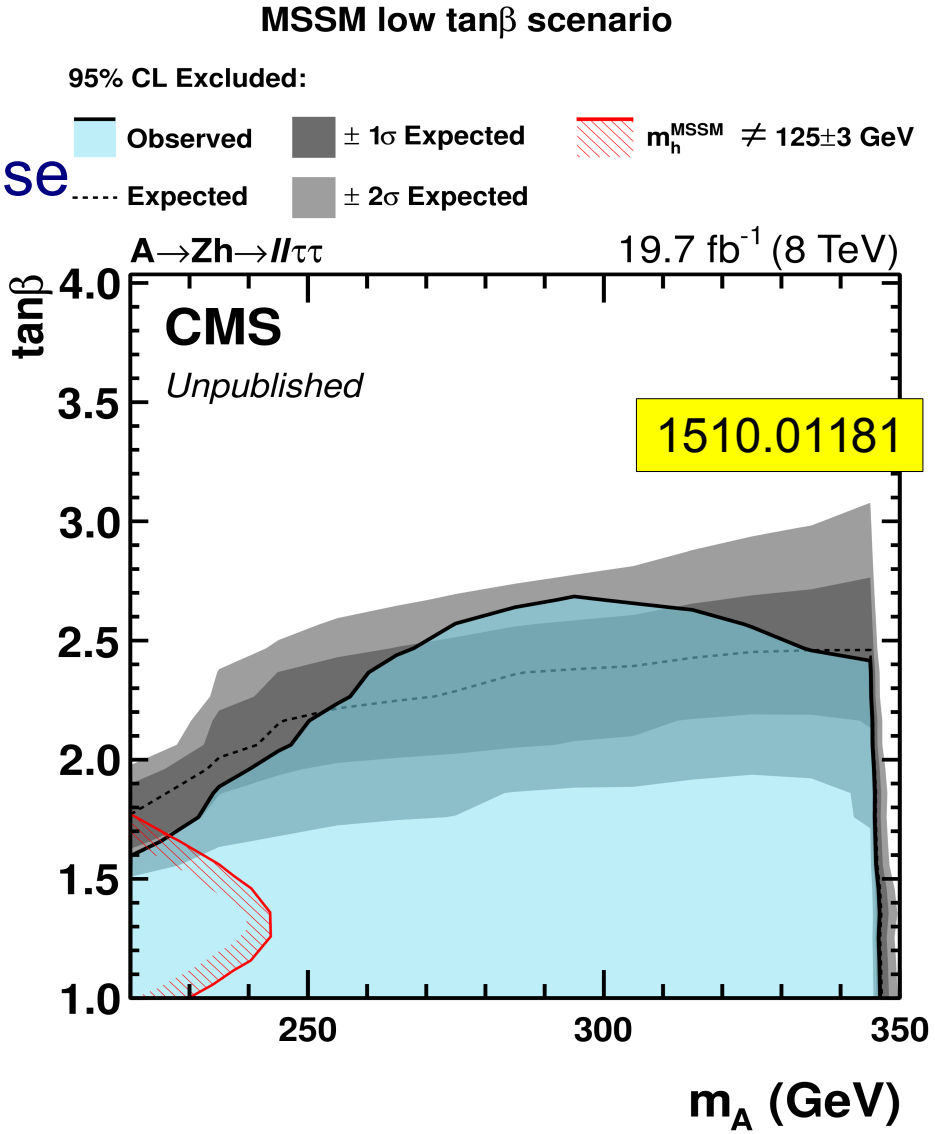
Strong dependence on Higgsino mass parameter μ and thus bottom Yukawa coupling



A→Zh Searches

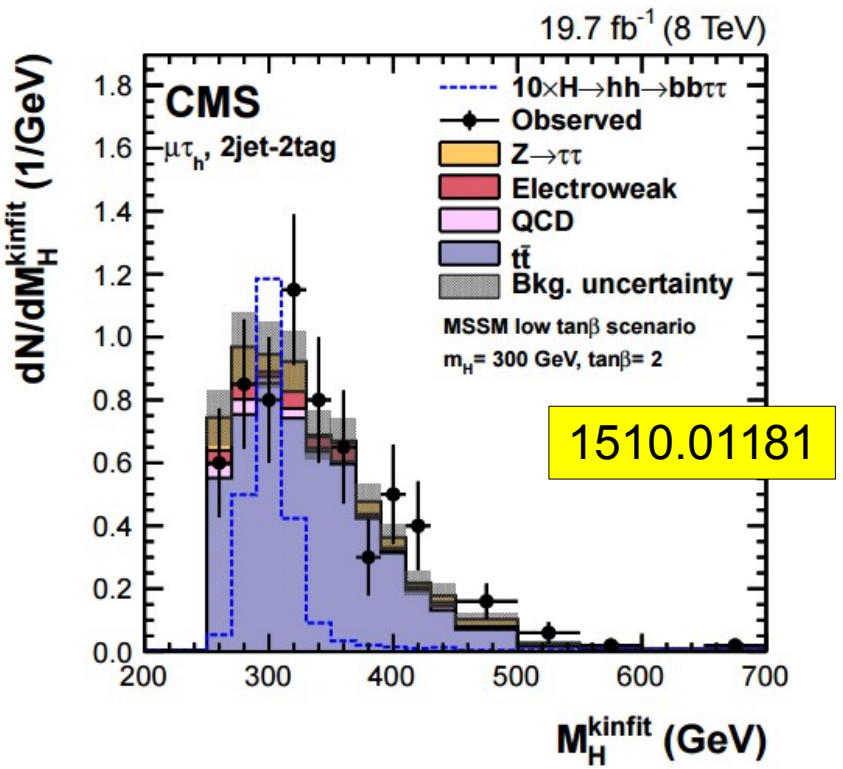
- For low tanβ, A→Zh and H→hh when $m_{Z/h}+m_h<m_{A/H}<2m_t$
  - Extends beyond limit depending on parameters in 2HDMs
- CMS search in llbb̄ and llττ
  - Slightly better reach in llbb, but combine with H→hh in latter case
- ATLAS use ννbb̄ for large m_A
  - No llττ at 13 TeV yet

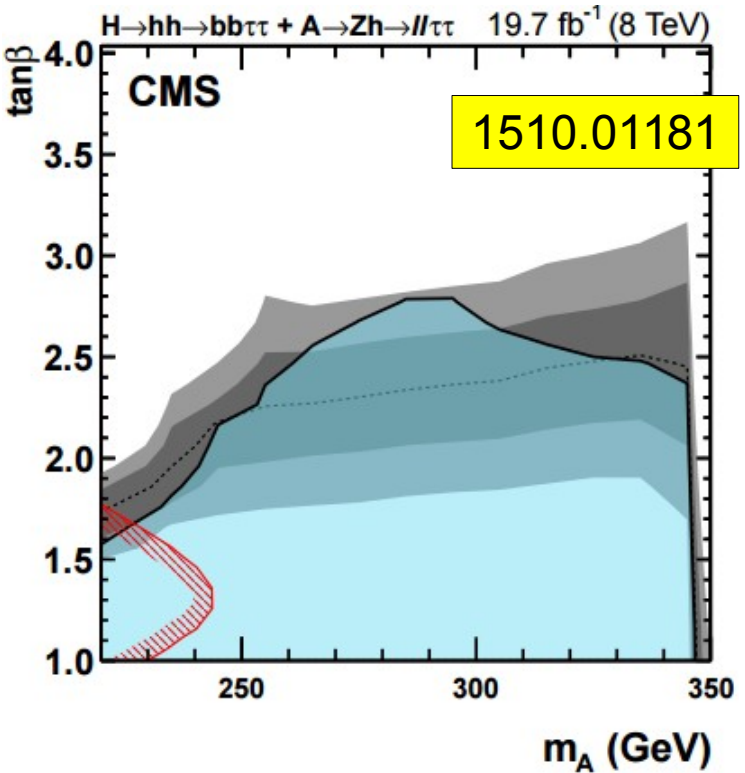




H→hh Searches

- Di-higgs resonances searched for in multiple h decays
- ATLAS and CMS have searches for hh→bb̄bb̄ at both 8 and 13 TeV, but they have poor sensitivity at low mass
  - Normally interpreted as search for example for a KK-graviton, and not in extended Higgs scenarios
- Searches for H→hh→bb̄ττ can go to lower mass
  - Use kinematic fit to improve di-higgs mass resolution

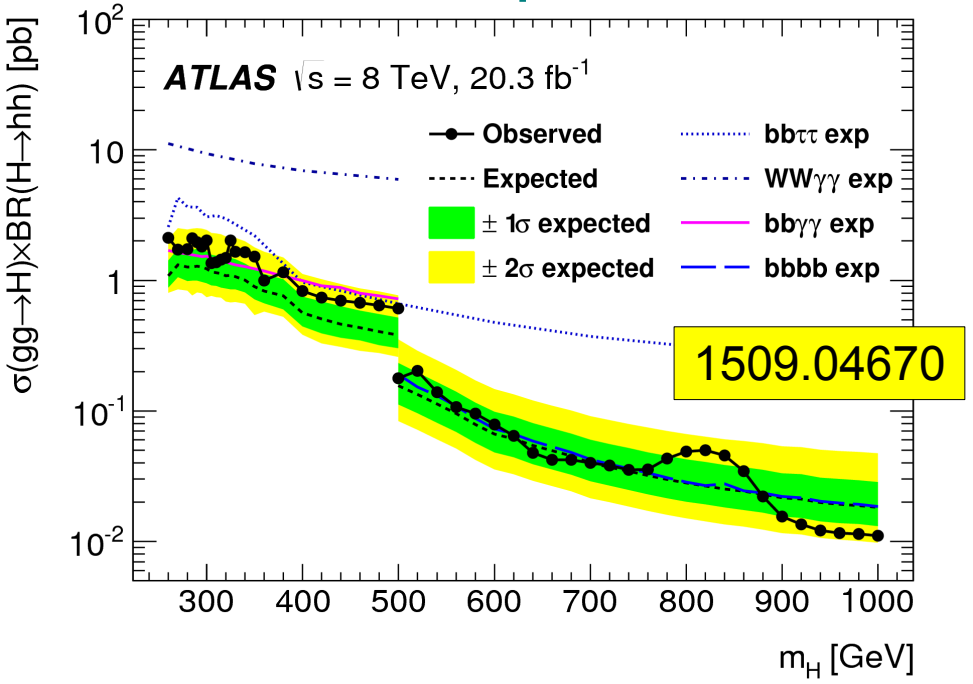


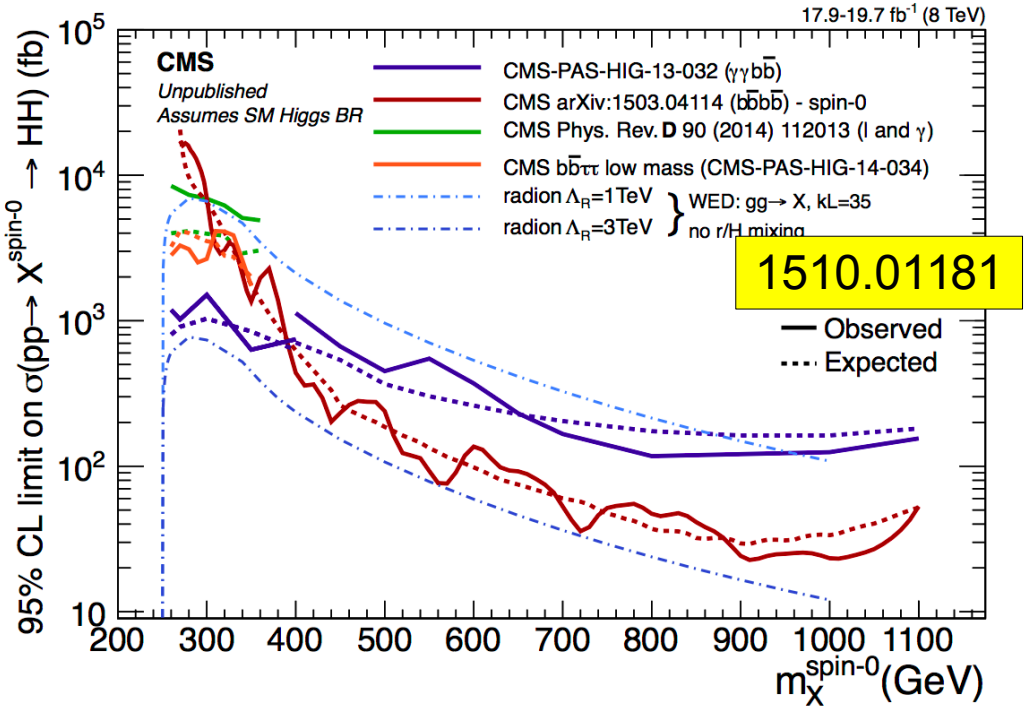


H→hh Searches

- At low mass, bbγγ most sensitive despite low γγ BF
  - Low backgrounds, largely data-driven using mass sidebands in $m_{b\bar{b}}$, $m_{\gamma\gamma}$ and $m_{\gamma\gamma b\bar{b}}$, the latter after p_T rescaling to give m_h mass (CMS uses MC for single Higgs background)
- Also searches in bbWW and γγWW, but not competitive

Comparison of hh channels at 8 TeV





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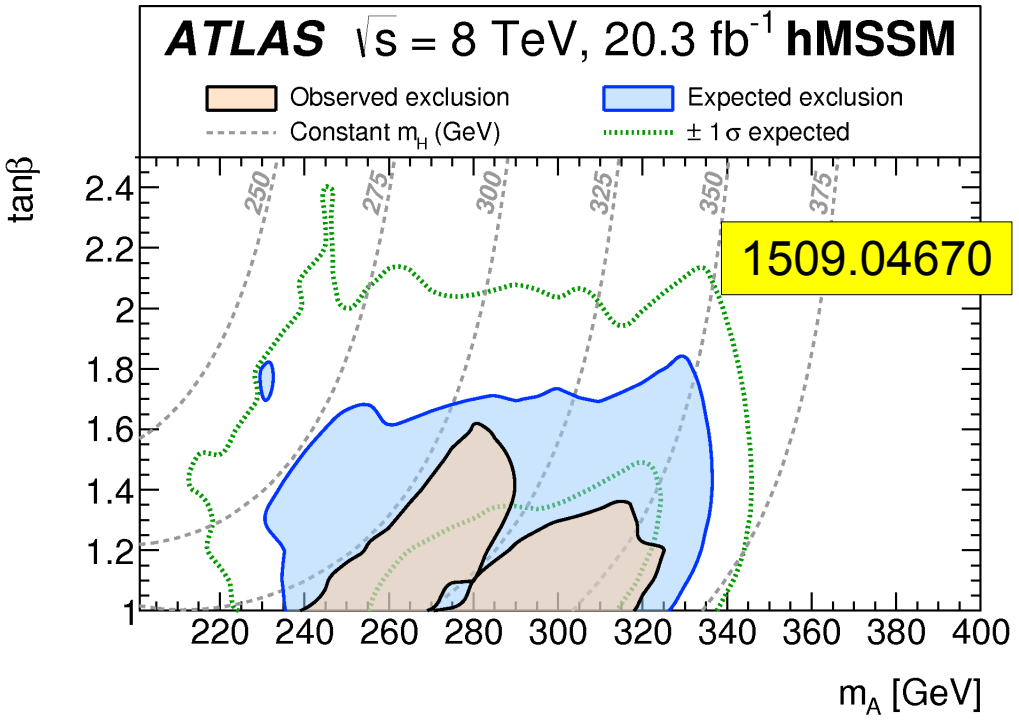
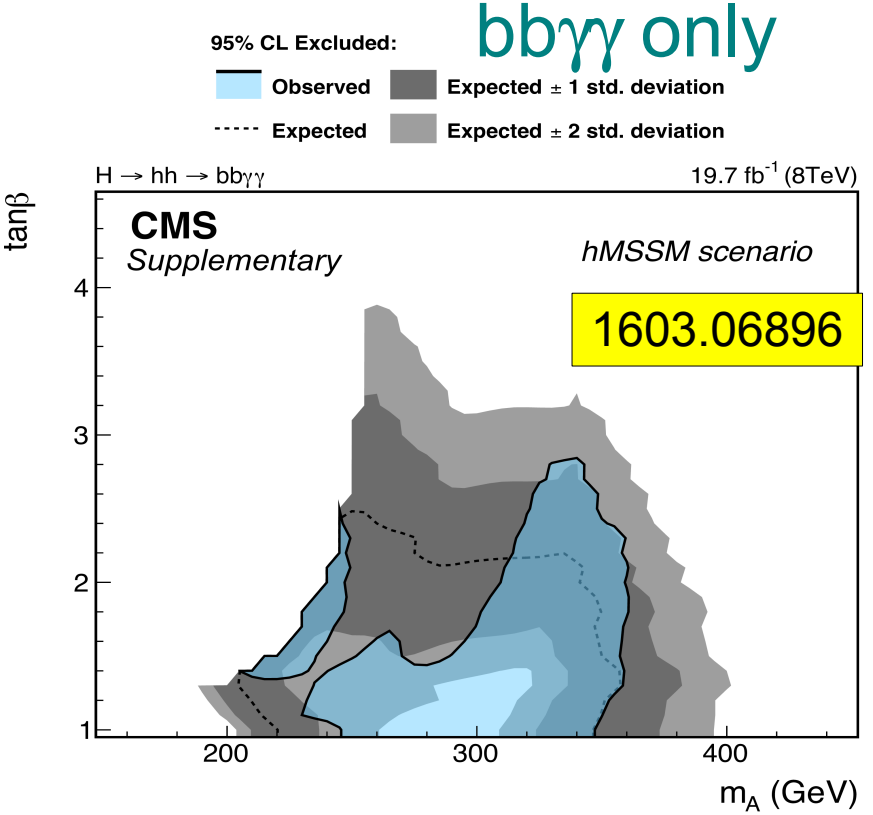
Combination of hh channels:



bbγγ only



H→VV Searches

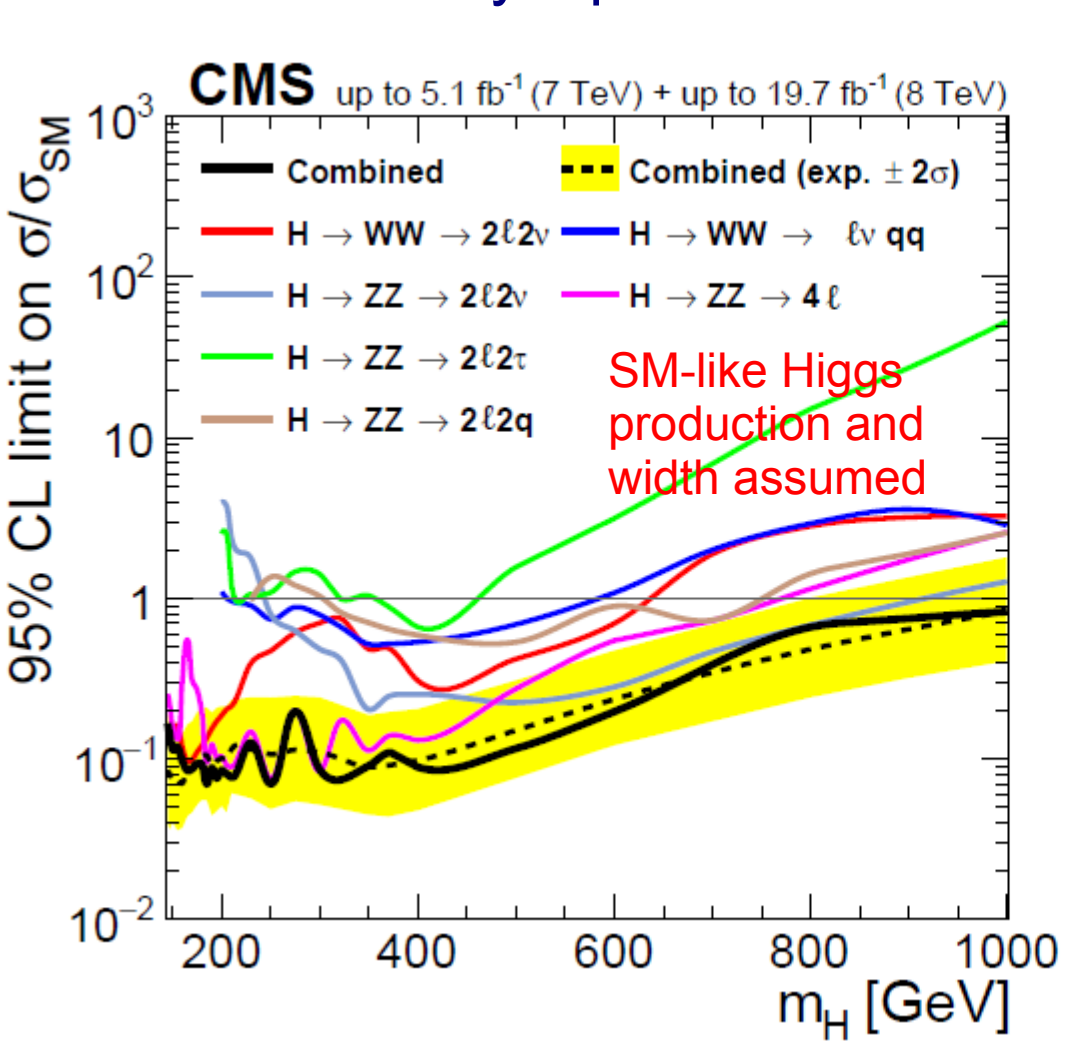
- Also have H→WW/ZZ decays at low tanβ
- Large set of channels when splitting by decay modes and between gluon-fusion and VBF production

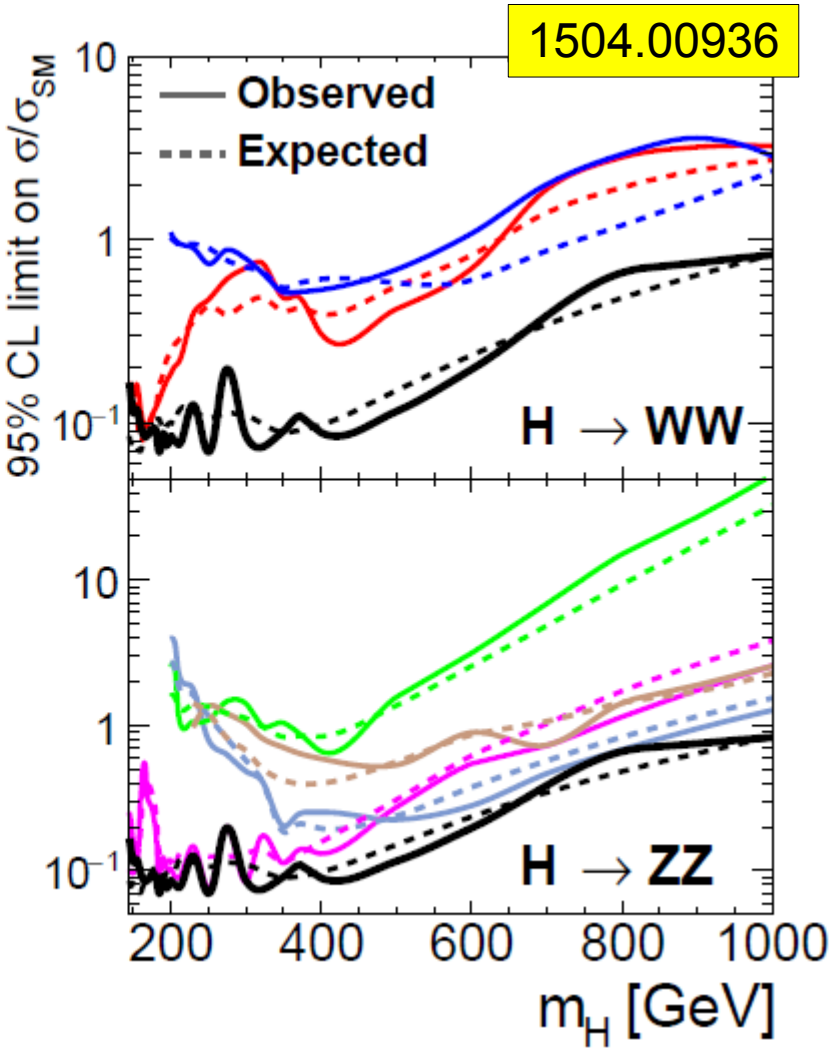
CMS 1504.00936

H decay mode	H production	Exclusive final states	No. of channels	m_H range [GeV]	m_H resolution
$WW \to \ell\nu\ell\nu$	untagged	((ee, $\mu\mu$), eμ) + (0 or 1 jets)	4	145–1000 [a,b]	20%
	VBF tag	((ee, $\mu\mu$), eμ) + $(jj)_{VBF}$	2	145–1000 [a,b]	20%
$WW \to \ell\nu qq$	untagged	(eν, $\mu\nu$) + $(jj)_W$	2	180–600	5–15%
	untagged	(eν, $\mu\nu$) + $(J)_W$ + (0+1-jets)	2	600–1000 [b]	5–15%
	VBF tag	(eν, $\mu\nu$) + $(J)_W$ + $(jj)_{VBF}$	1	600–1000 [b]	5–15%
$ZZ \to 2\ell 2\ell'$	untagged	4e, 4μ, 2e2μ	3	145–1000	1–2%
	VBF tag	(4e, 4μ, 2e2μ) + $(jj)_{VBF}$	3	145–1000	1–2%
	untagged	(ee, $\mu\mu$) + ($\tau_h\tau_h$, $\tau_e\tau_h$, $\tau_\mu\tau_h$, $\tau_e\tau_\mu$)	8	200–1000	10–15%
$ZZ \to 2\ell 2\nu$	untagged	(ee, $\mu\mu$) + (0 or $\geq$ 1 jets)	4	200–1000	7%
	VBF tag	(ee, $\mu\mu$) + $(jj)_{VBF}$	2	200–1000	7%
$ZZ \to 2\ell 2q$	untagged	(ee, $\mu\mu$) + $(jj)_Z^{0,1,2\,b\,tags}$	6	230–1000 [c]	3%
	untagged	(ee, $\mu\mu$) + $(J)_Z^{0,1,2\,b\,tags}$	6	230–1000 [c]	3%
	VBF tag	(ee, $\mu\mu$) + $(jj)_Z^{0,1,2\,b\,tags}$ + $(jj)_{VBF}$	6	230–1000 [c]	3%
	VBF tag	(ee, $\mu\mu$) + $(J)_Z^{0,1,2\,b\,tags}$ + $(jj)_{VBF}$	6	230–1000 [c]	3%

H→VV Searches

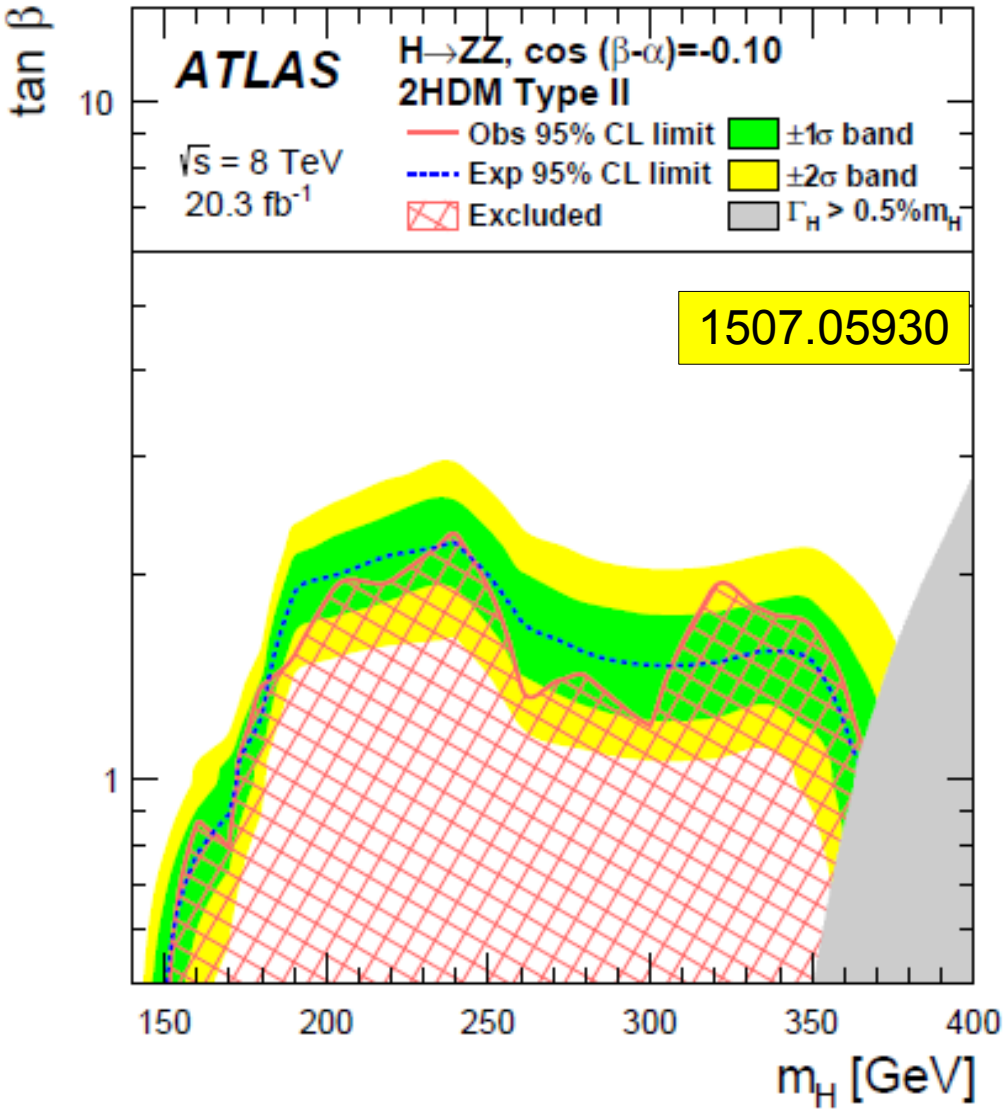
- Results in different channels are combined
  - Low mass region most interesting for MSSM case
  - Dominated by leptonic channels

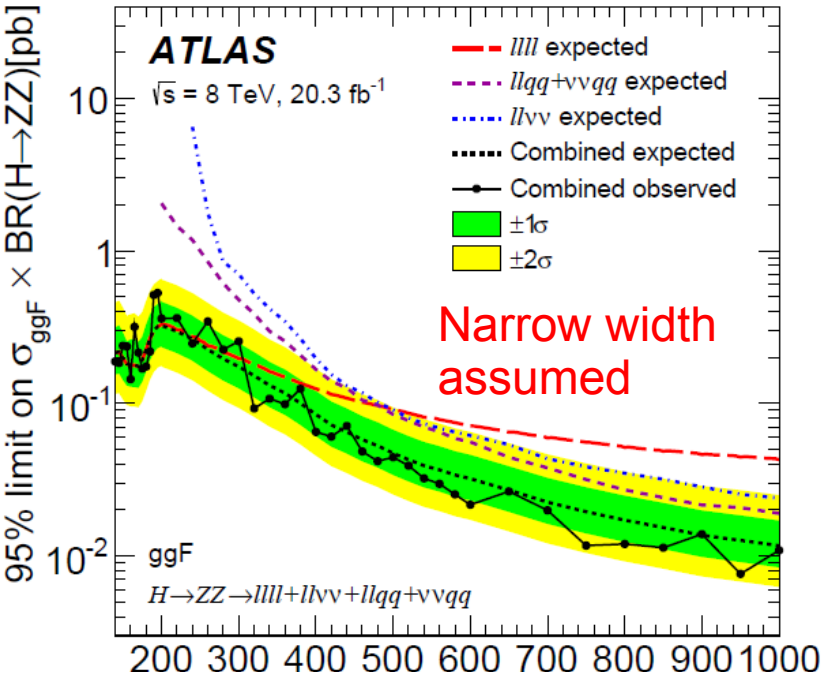


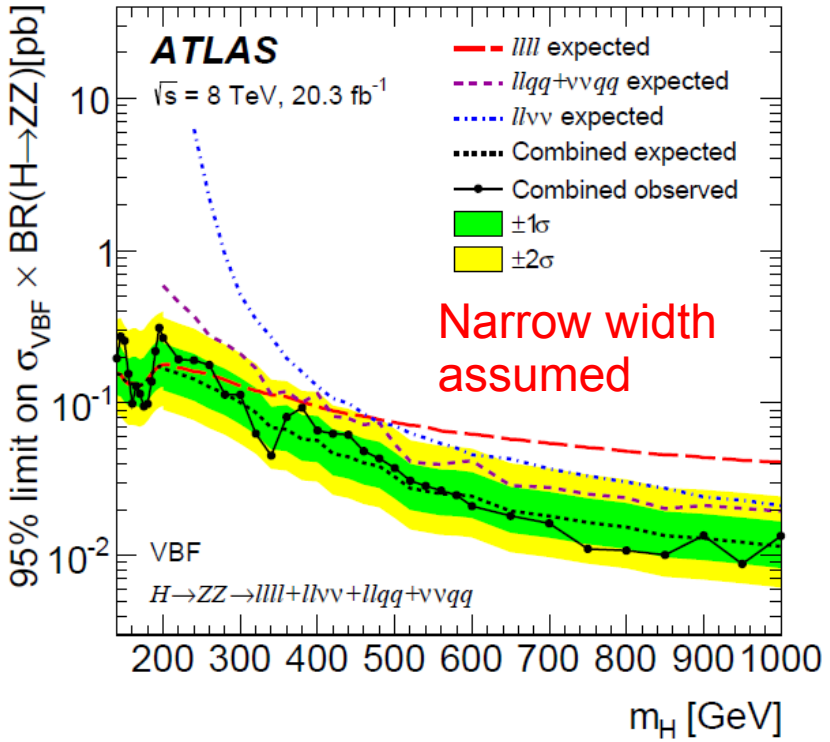


H→VV Searches

- Similar set of ATLAS searches
  - Exclusion shown in non-MSSM 2HDM Type-II model

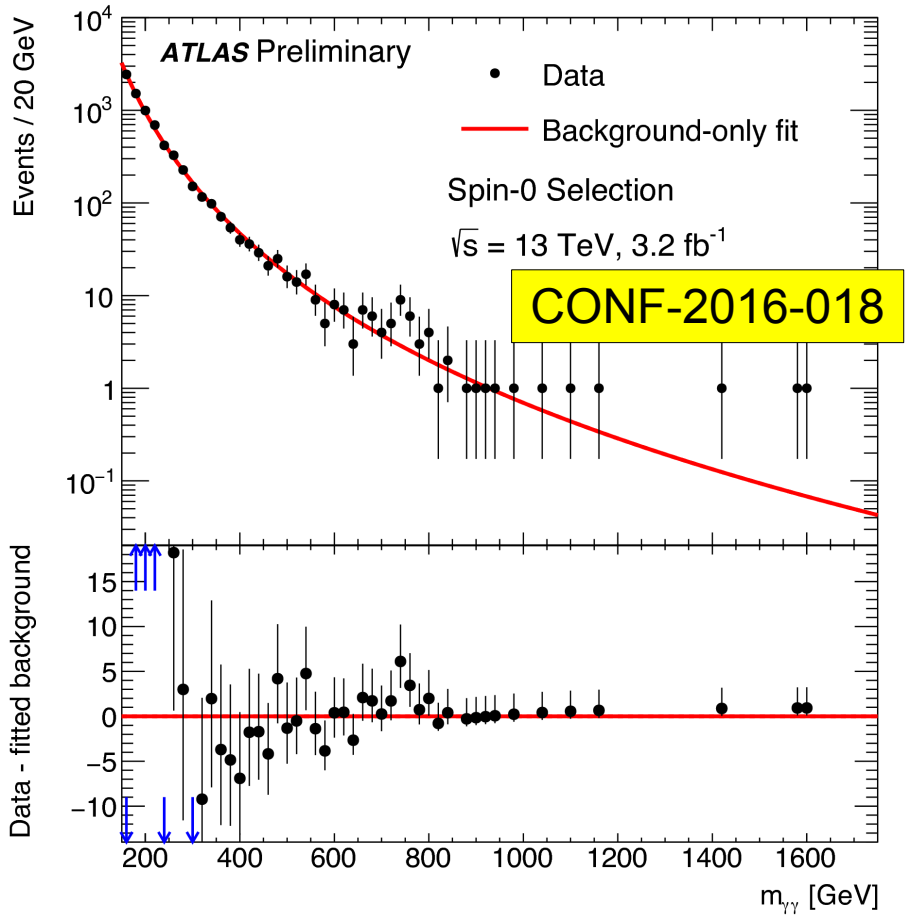


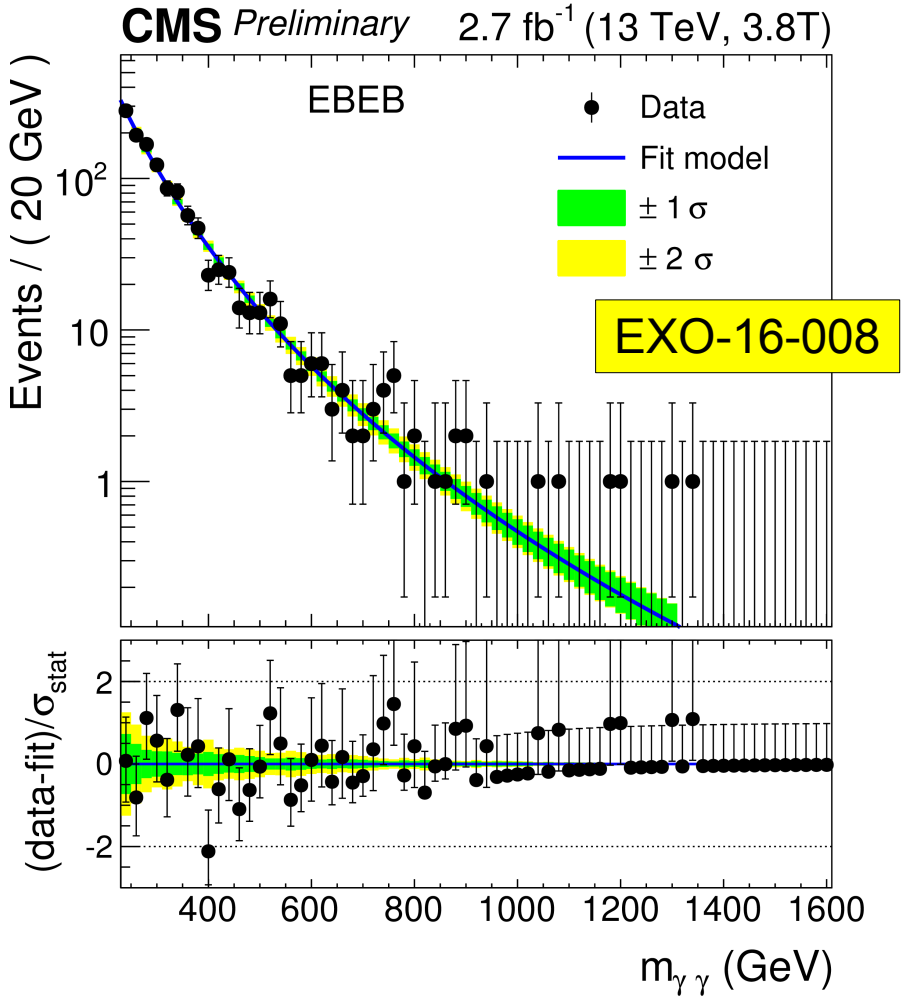




X→γγ/Zγ Searches

- Lots of interest in heavy scalar decays to γγ recently
  - If signal is real, cannot be accommodated in regular MSSM

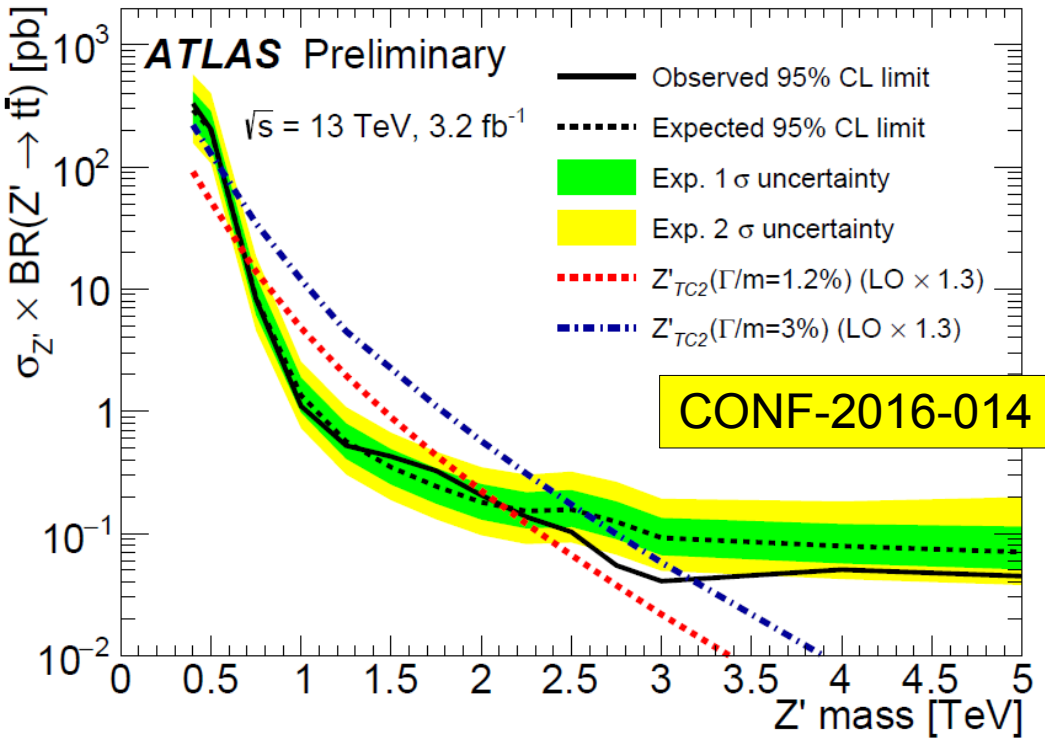


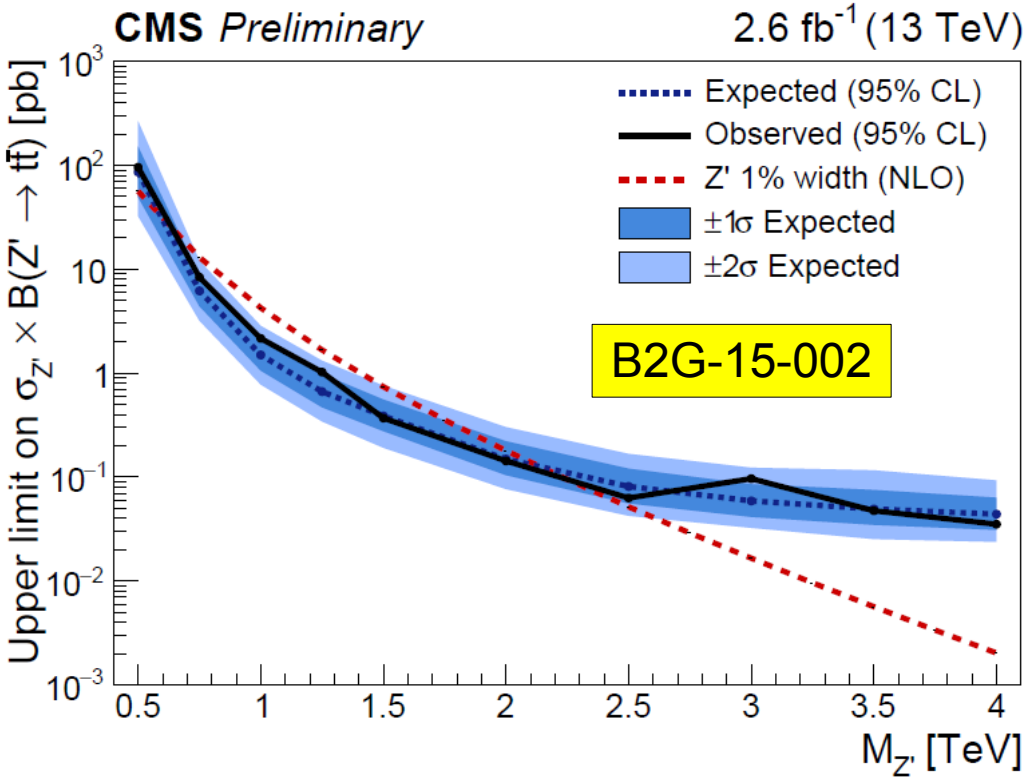


- Also searches in Zγ, but no excesses seen

A/H→$t\bar{t}$ Searches?

- For low tanβ, $m_A > 2m_{top}$, A/H→$t\bar{t}$ dominant decay mode
- Difficult channel, particularly at low m_A due to large non-resonant background (also have interference)
- No 8/13 TeV LHC results targeting heavy Higgs to $t\bar{t}$
  - Focus more on other heavier, narrow resonances



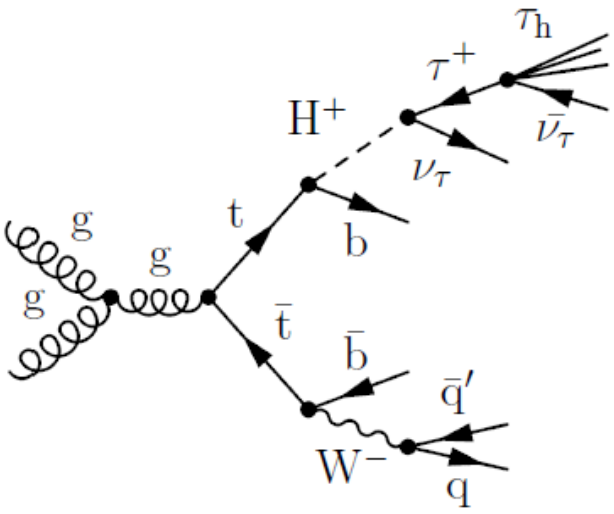


Is it possible to target also (lightish) H→$t\bar{t}$?

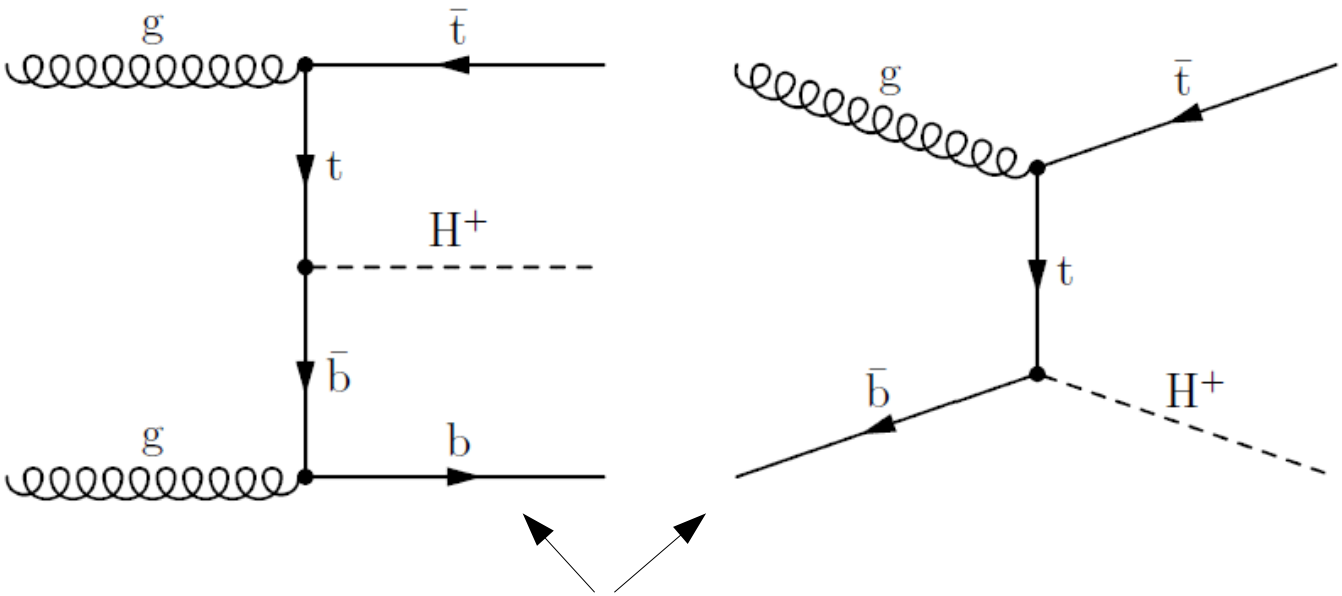
$H^+ \to \tau\nu$ Searches

- Main channel for charged Higgs search
- Split by production mode depending m_{H+}

In top decay



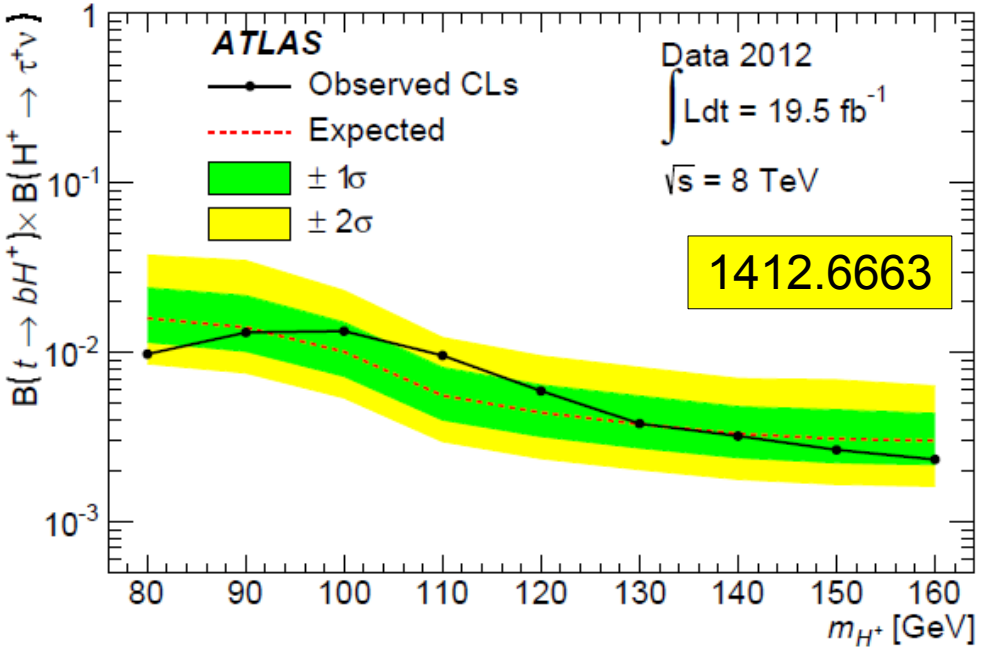
Top-associated production

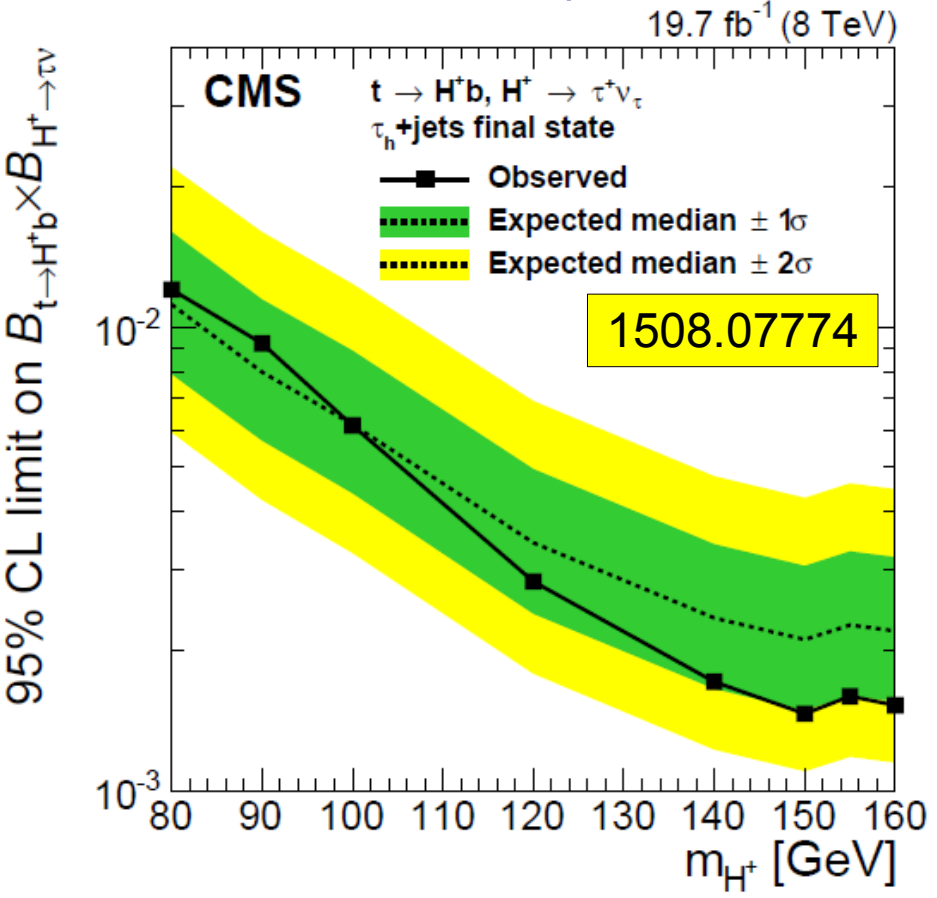


Match 4FS and 5FS NLO calculations using “Santander matching scheme”

$H^+ \to \tau\nu$ Searches, $m_{H+} < m_{top}$

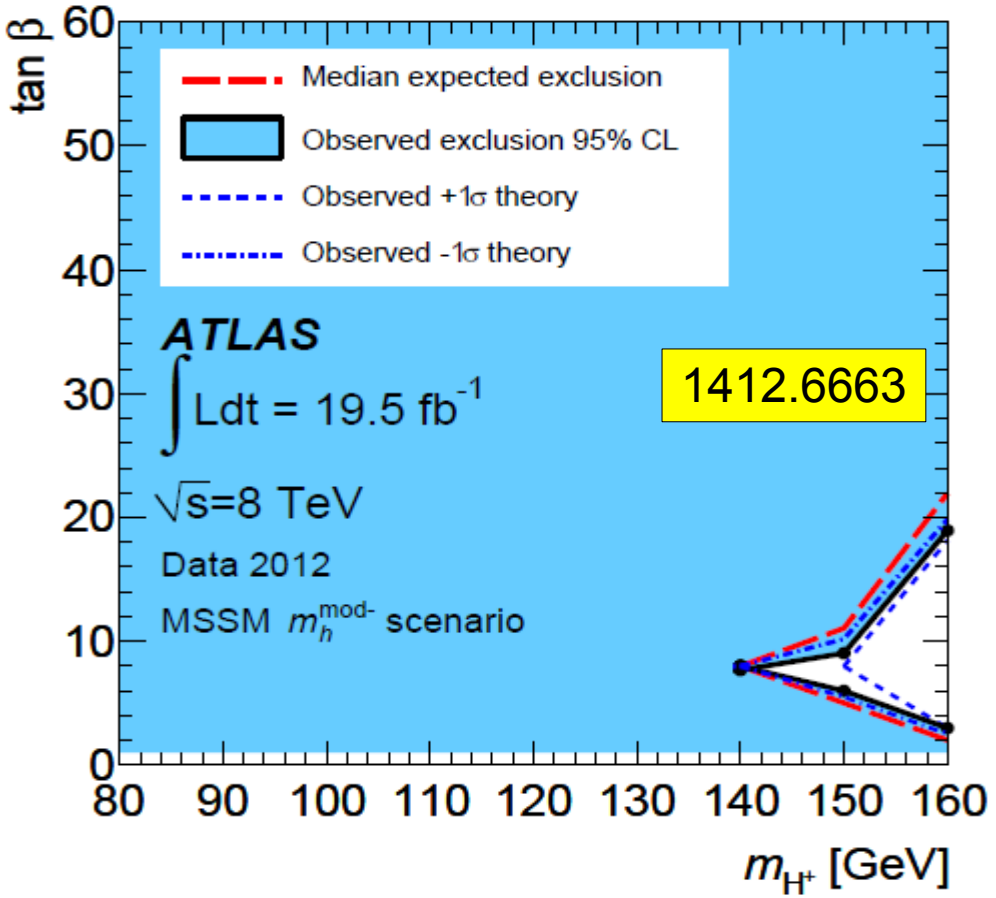
- Dominant decay mode for tanβ>~3
- Select only hadronic top and τ decay modes
  - Main discriminating variable: $m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\tau} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos \Delta\phi_{\tau,\mathrm{miss}})}$
  - Main backgrounds (EW and tt) estimated with τ-embedding (replacing muon with simulated taus in data events)

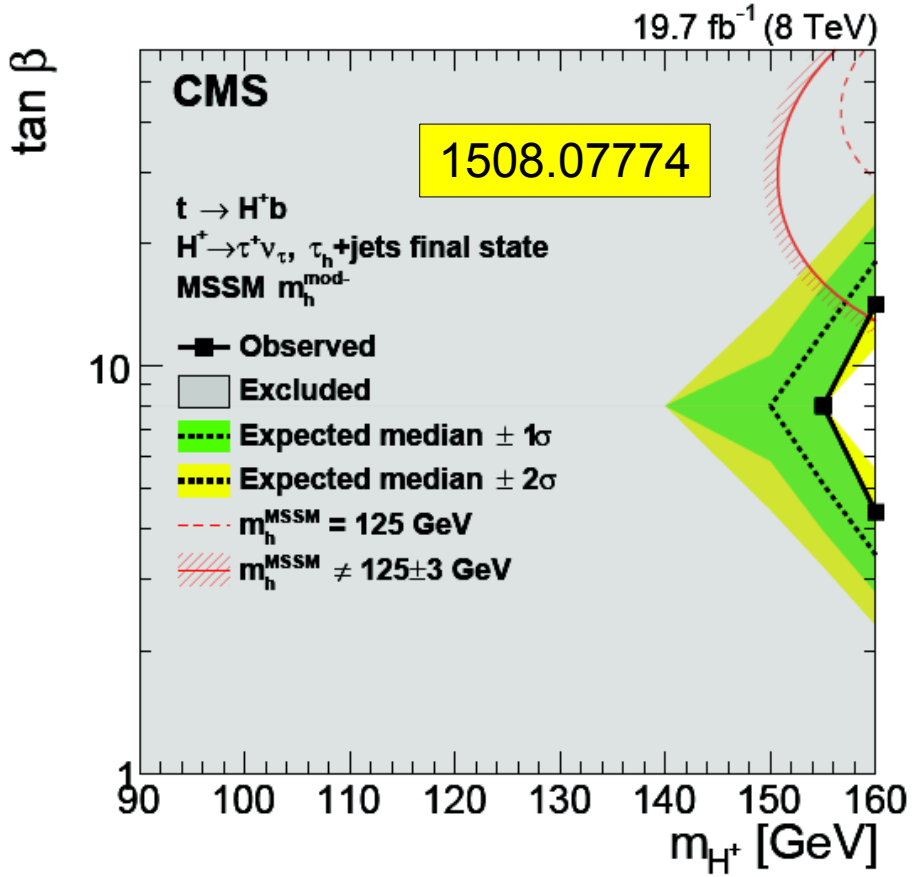




$H^+ \to \tau\nu$ Searches, $m_{H+} < m_{top}$

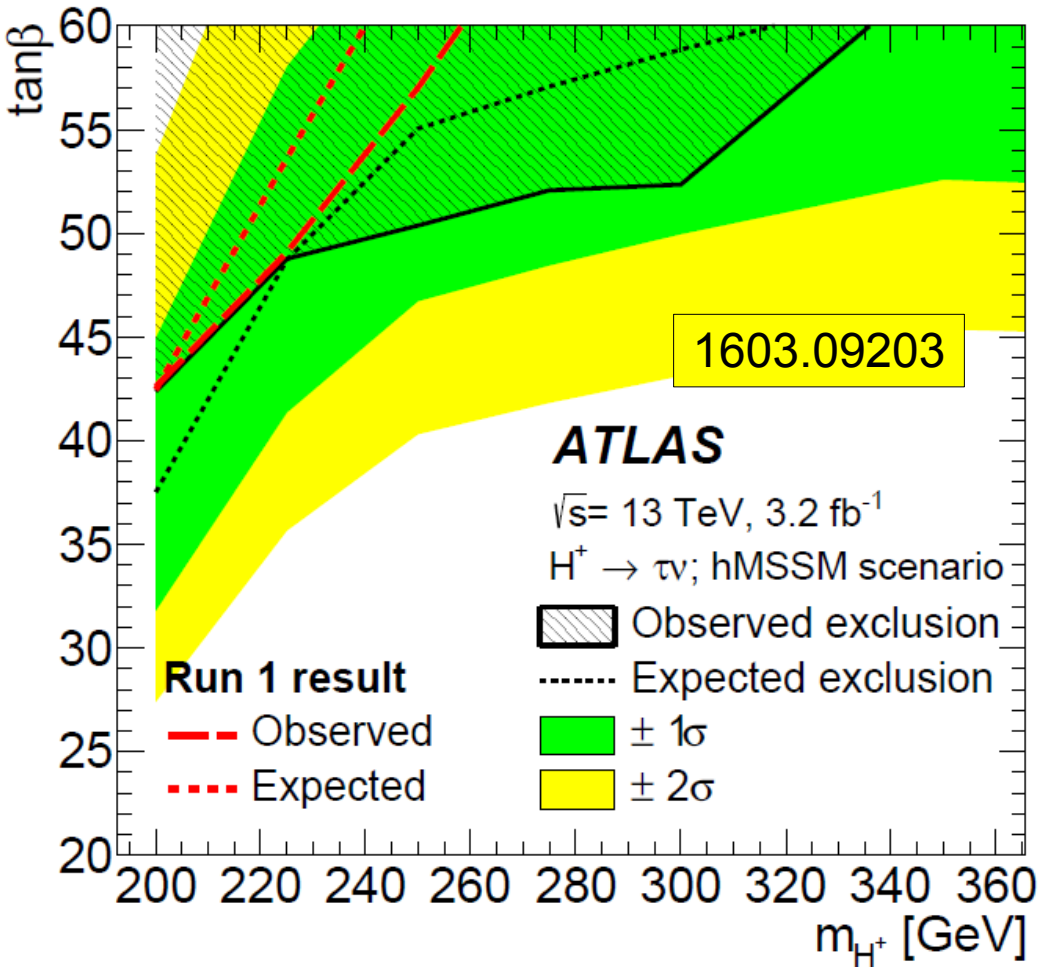
- Dominant decay mode for tanβ>~3
- Select only hadronic top and τ decay modes
  - Main discriminating variable: $m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\tau} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos \Delta\phi_{\tau,\mathrm{miss}})}$
  - Main backgrounds (EW and tt) estimated with τ-embedding (replacing muon with simulated taus in data events)

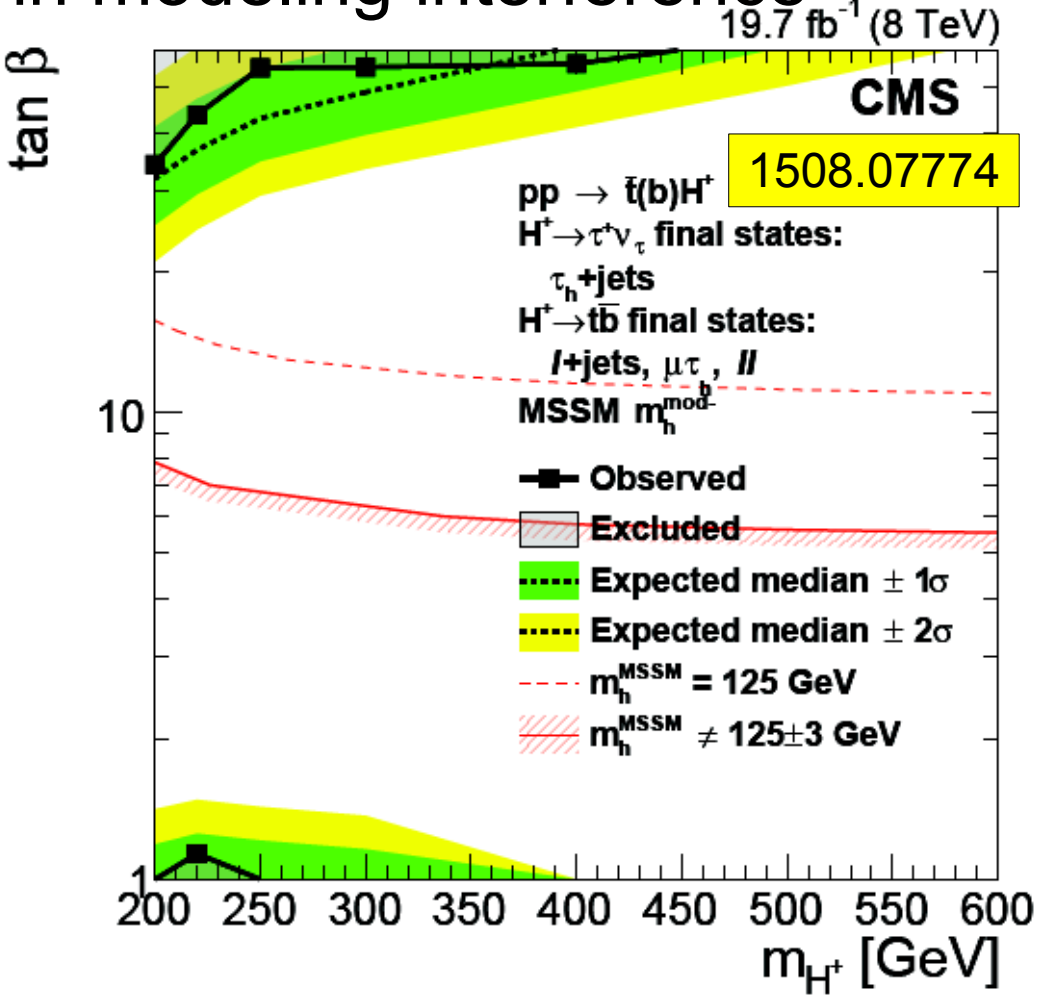




$H^+ \to \tau\nu$ Searches, $m_{H+} > m_{top}$

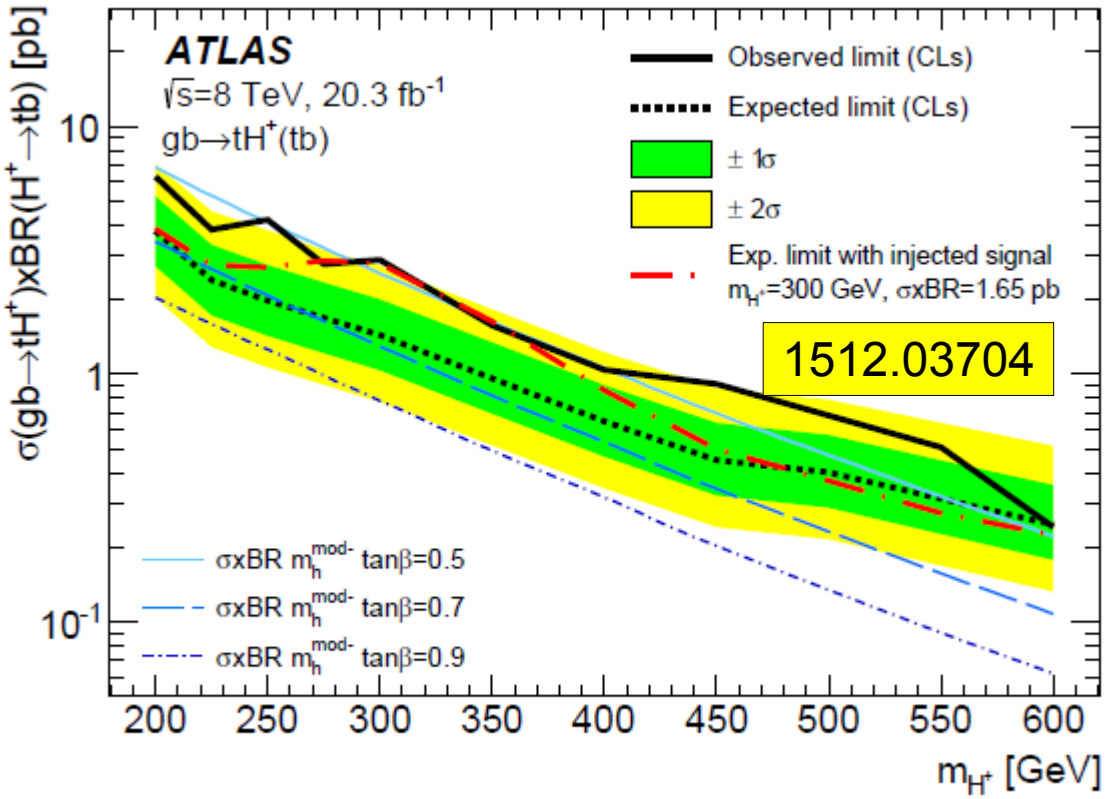
- For high mass CMS considers additional decay modes
  - $\mu\tau_{had}$, ℓ+jets and $\ell\ell'$ – adds sensitivity to $H^+ \to tb$ as well
  - Combined limits in specific MSSM scenarios
- Note no interpretation between 160 and 200 GeV due to theoretical uncertainties in modeling interference

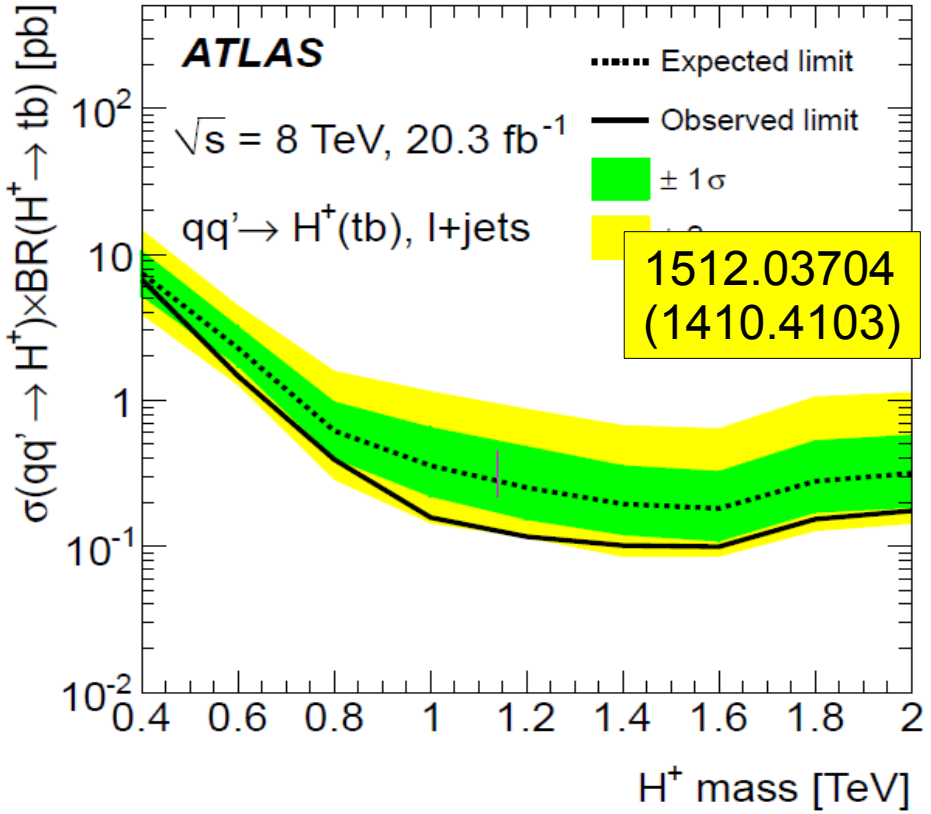




$H^+ \rightarrow tb$ Searches

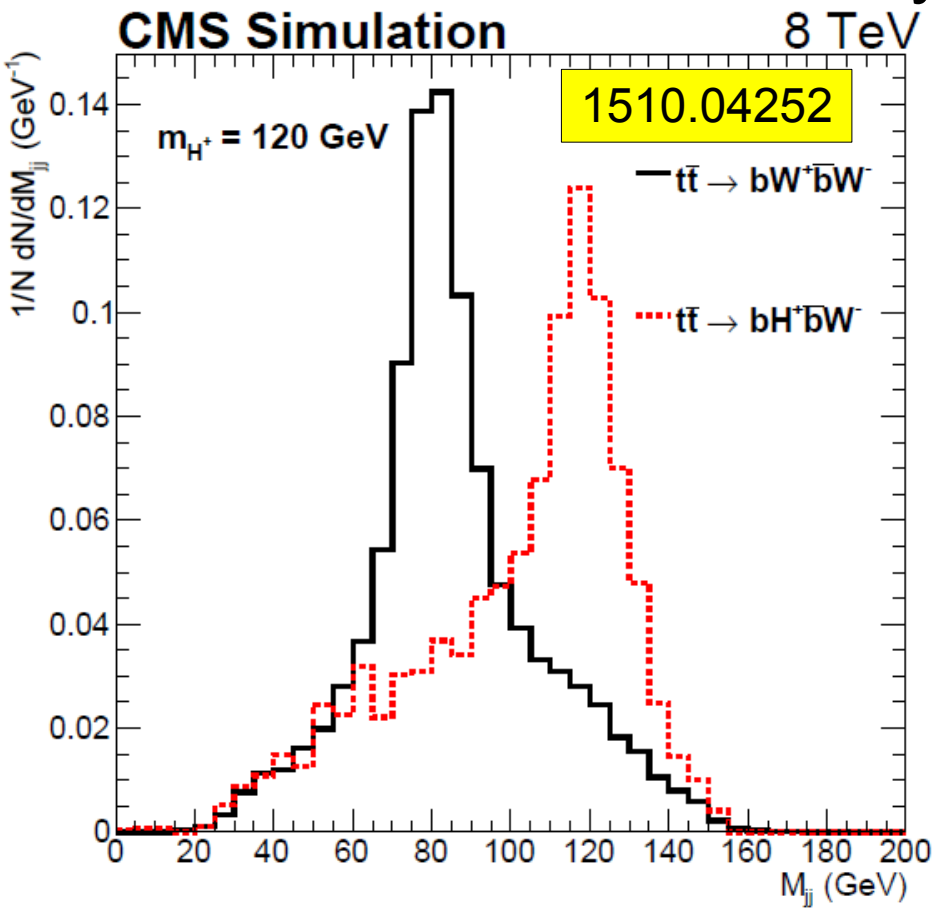
- Search for $gb \rightarrow tH^+$ with one semi-leptonic top decay
  - Select signal events with 3 bjets
  - BDT used to discriminate against $t\bar{t}+b\bar{b}$
- Expected exclusion up to $\tan\beta \sim 0.6$ for $200 < m_{H^+} < 400$ GeV
- ATLAS also reinterpreted search for $qq' \rightarrow W' \rightarrow tb$ as s-channel production of H^+ ($cs \rightarrow H^+$)
  - No sensitivity yet to type-II HDM including MSSM

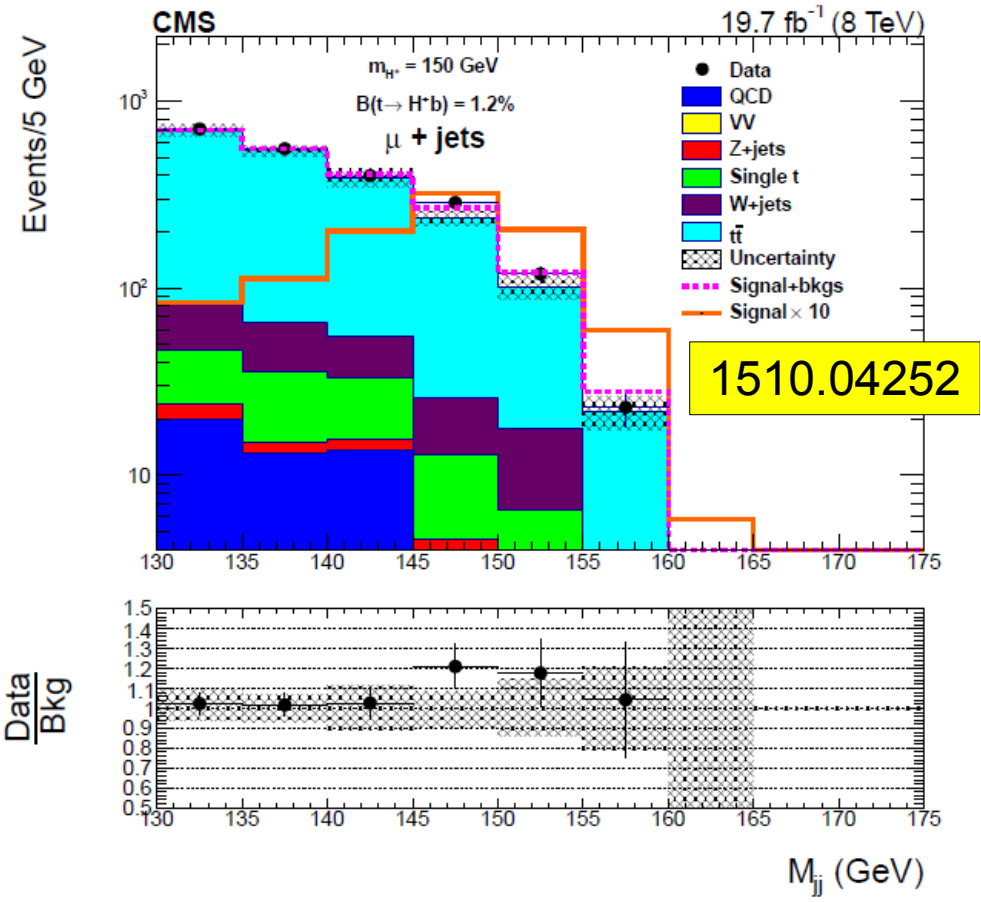




$H^+ \rightarrow cs$ Searches

- For $m_{H+} < m_{top}$ and $\tan\beta < 1$, $H^+ \rightarrow cs$ dominates (BF~70%)
- Search for in $t\bar{t}$ decay, with one $t \rightarrow b\ell\nu$ and one $t \rightarrow bH^+$
- Kinematic fit to fully reconstructed tt decay to obtain best possible di-jet mass to discriminate between hadronic W and H^+ decays





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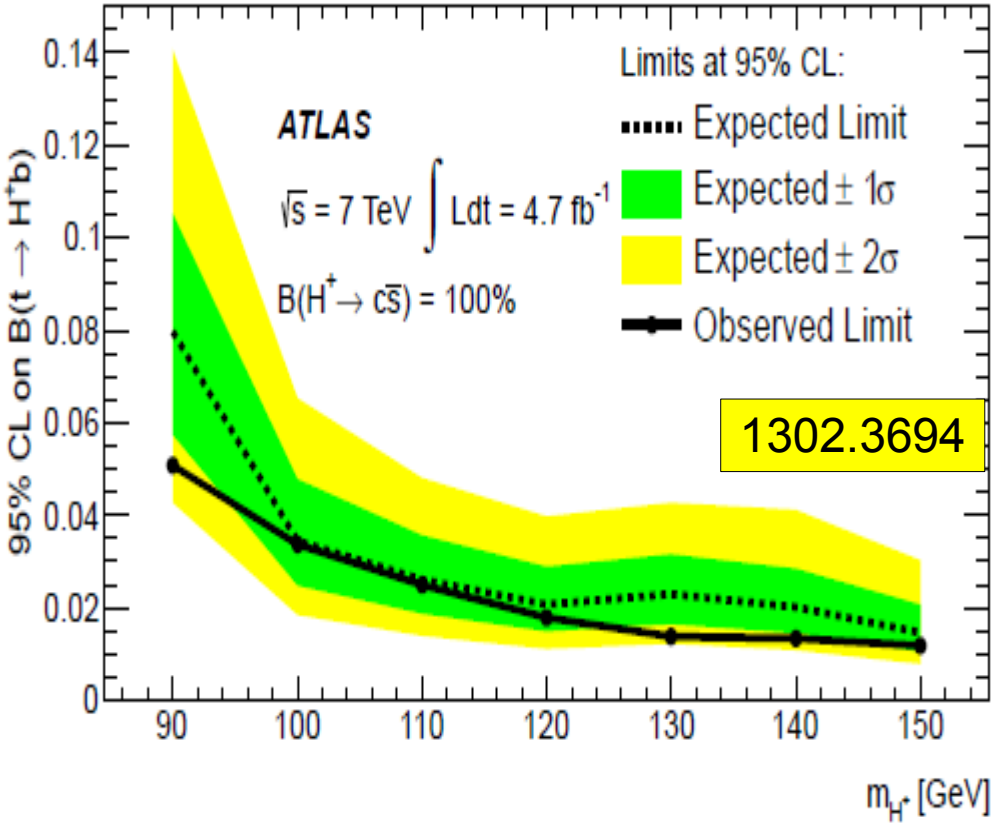
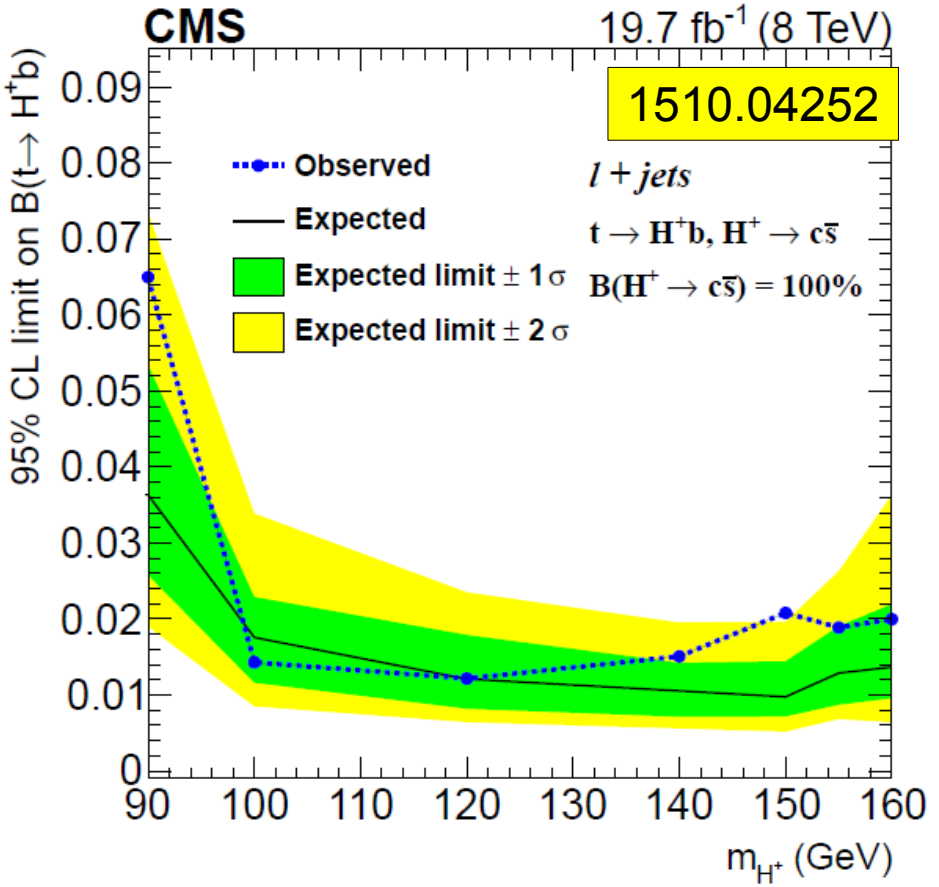
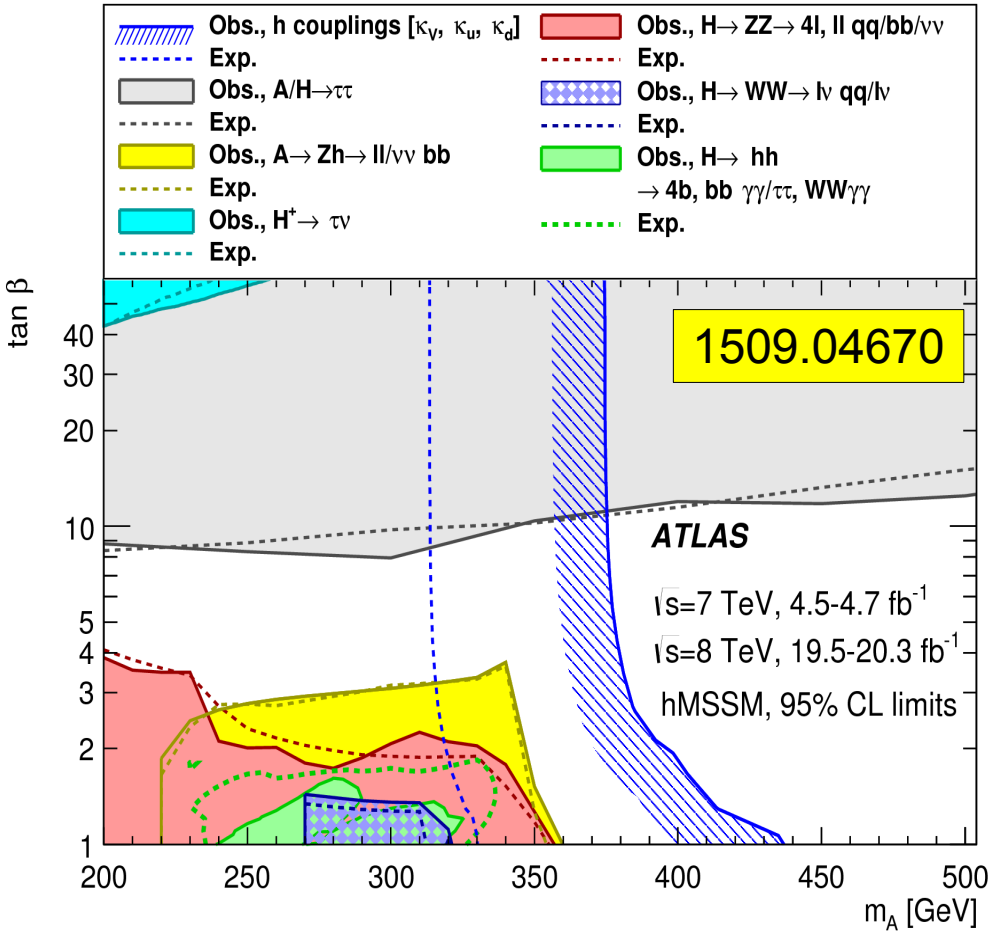
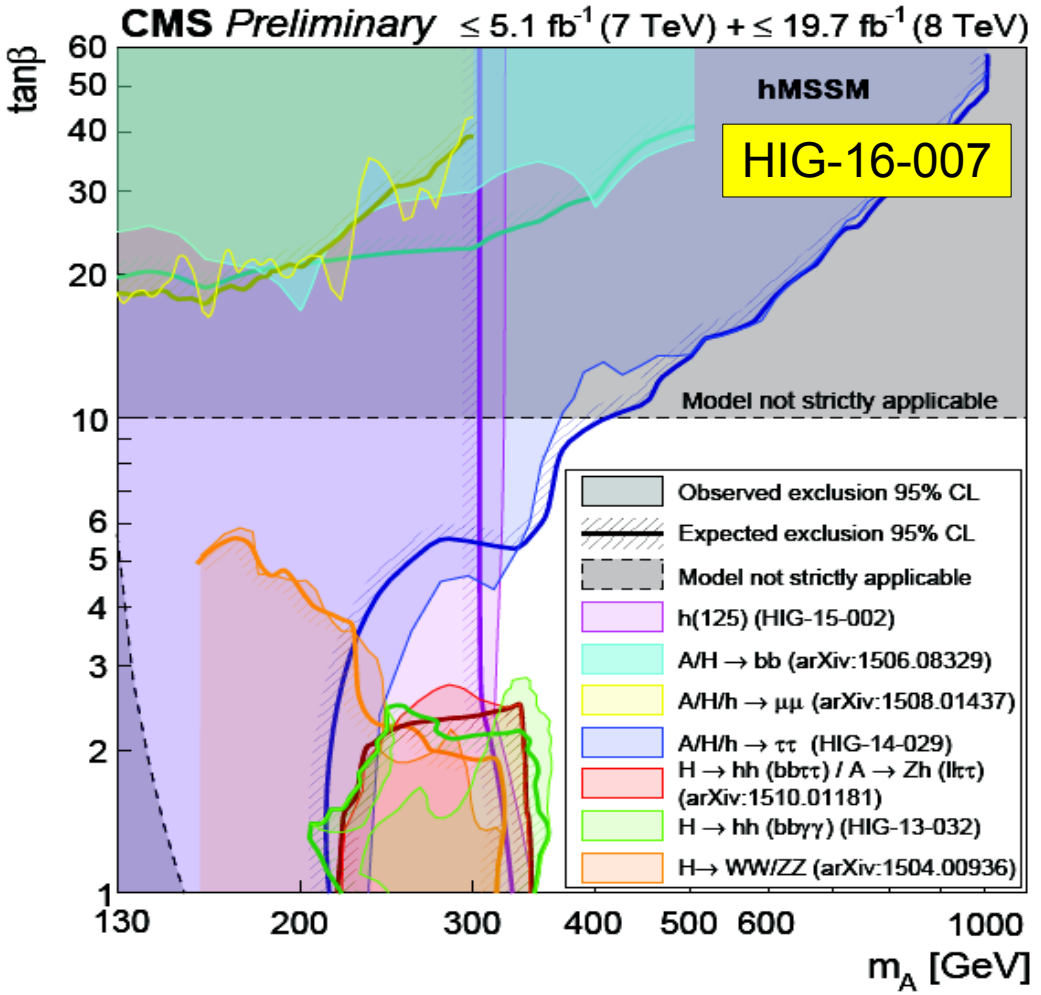




Summary of Exclusions in hMSSM

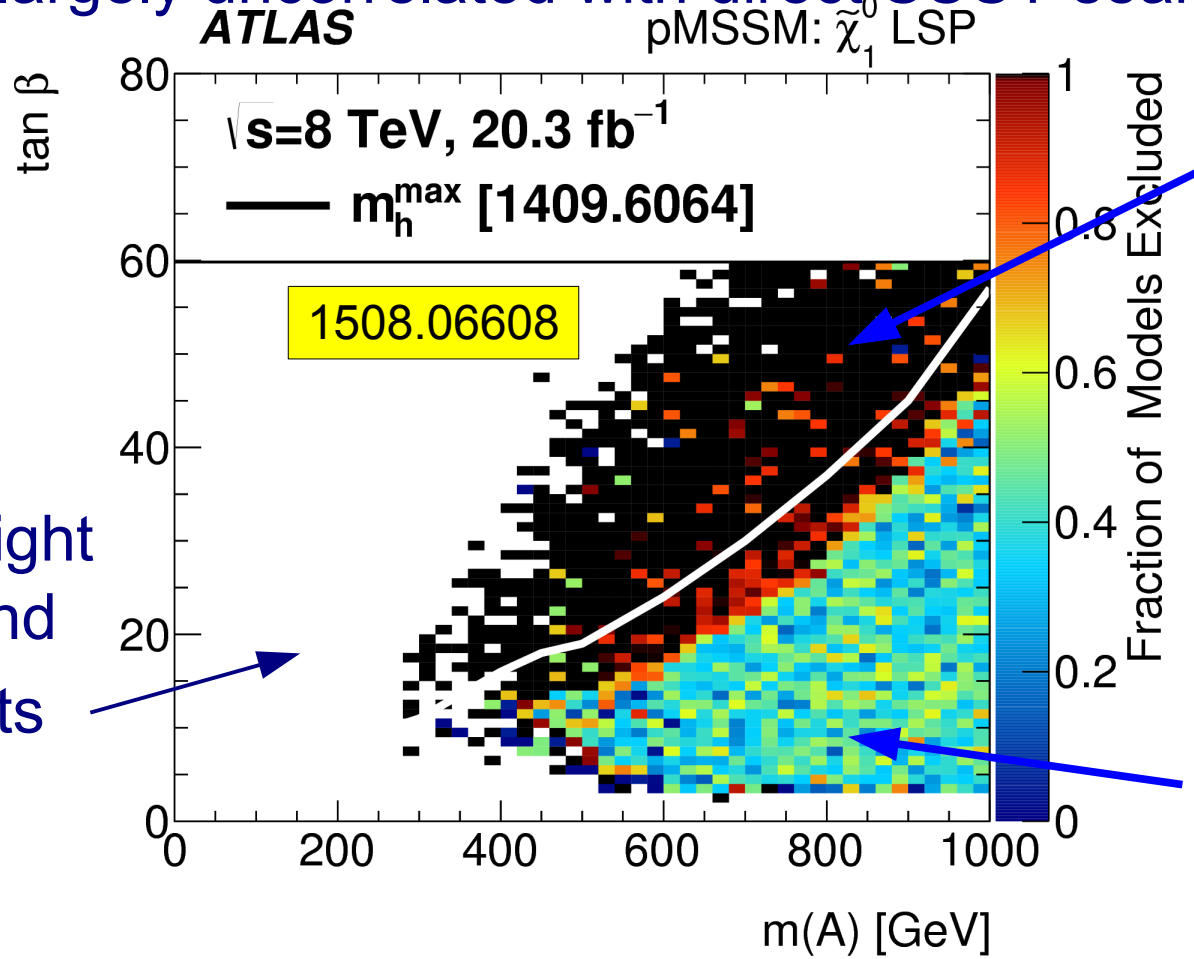
- 8 TeV searches have been reinterpreted in "hMSSM"
  - hMSSM uses m_h=125 GeV to set radiative corrections 1307.5205
- Allows direct comparison of ATLAS and CMS
  - Note that Higgs coupling fits largely exclude low m_A





Heavy Higgs in pMSSM

- ATLAS did scan over 19-parameter pMSSM in Run-1
  - Required that models satisfy most indirect constraints
  - 300k models with m_A<4 TeV and 1<tanβ<60
- ~40% excluded overall, ~2% by A/H→ττ search
  - A/H→ττ largely uncorrelated with direct SUSY searches



Few models with light m_A due to b→sγ and $B_s \rightarrow \mu\mu$ constraints

Excluded mostly by A/H→ττ search

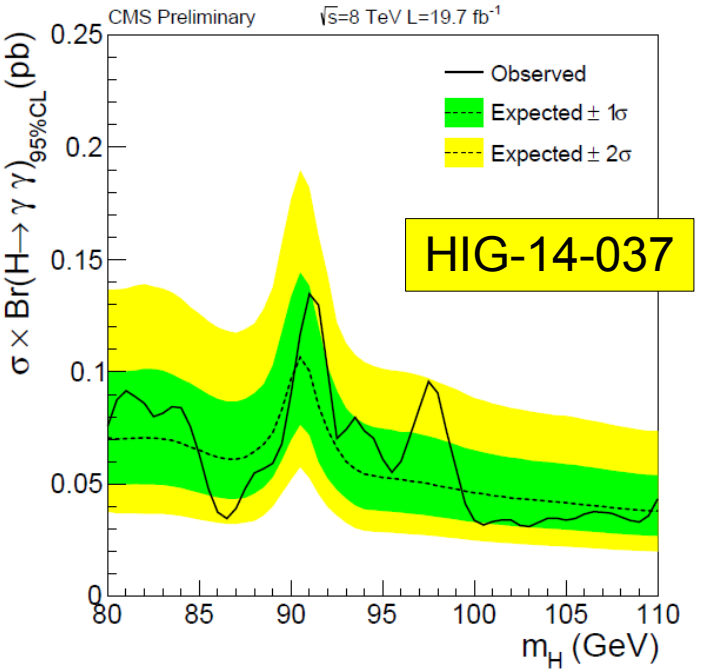
Fraction excluded by direct SUSY searchs

Light Scalar Searches (NMSSM)

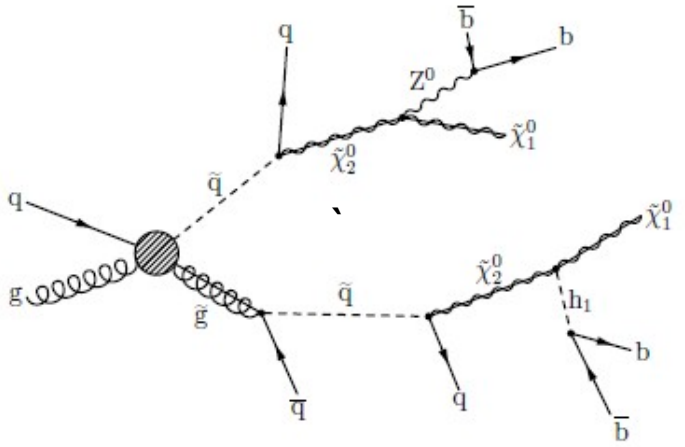
- Different decay and production modes considered

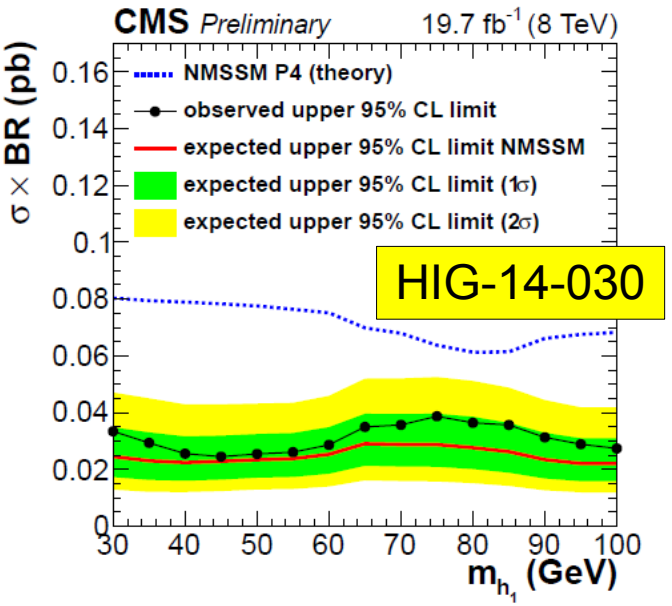
Light h→γγ

- In NMSSM σ·BR(h→γγ) could be up to 3.5 times higher than SM
- Extended SM search to lower masses:



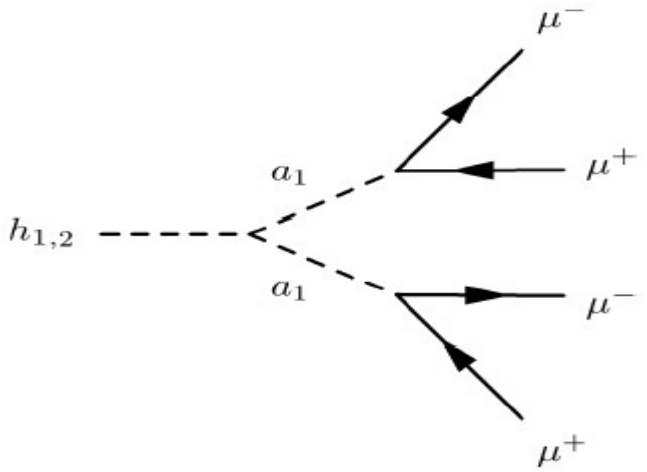
h→bb̄ in SUSY decay





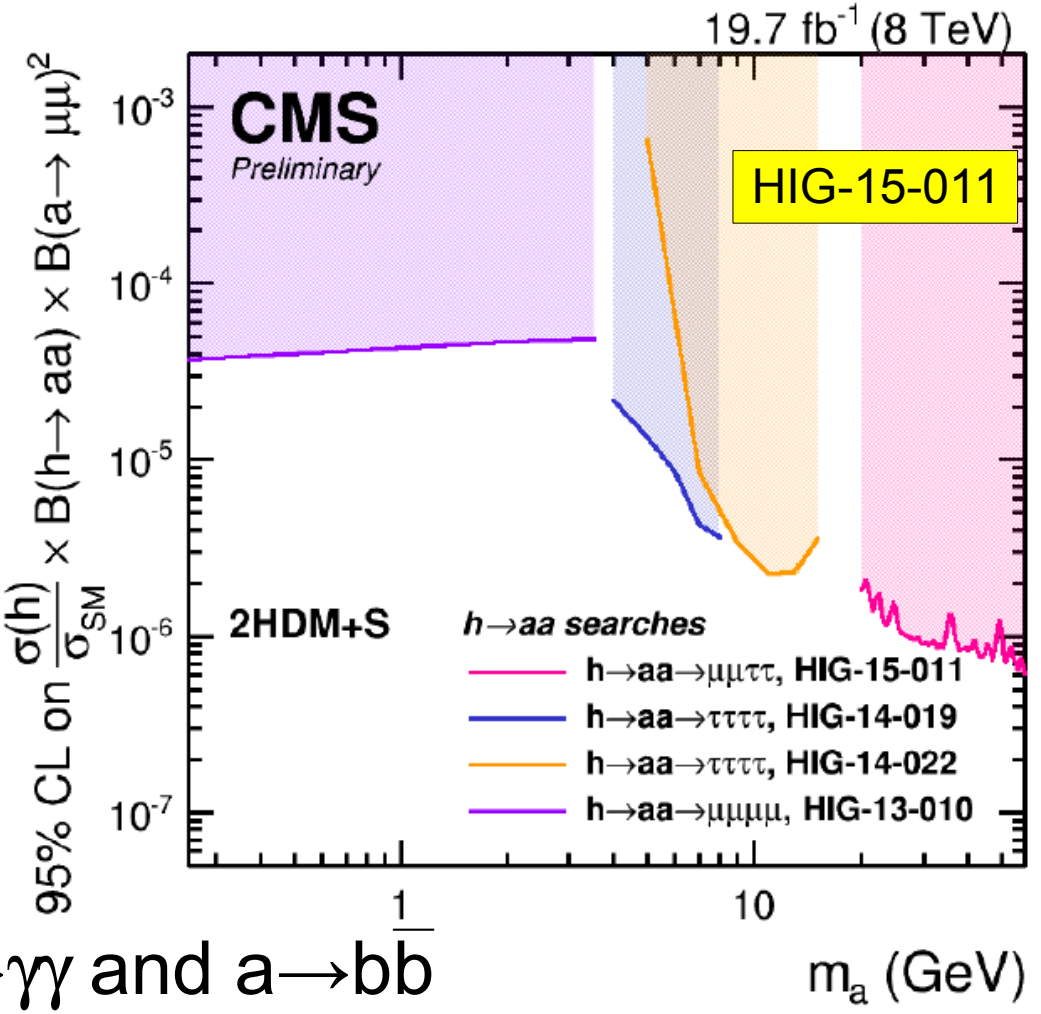
Light Scalar in Higgs Decay

- Most comprehensive effort is for pair produced pseudo-scalars in Higgs decays
  - Typically fit invariant dimuon/ditau mass to extract signal
  - Decay channel depends on kinematic range



- Compare using simple relationship

$$\frac{\Gamma(a \to \mu\mu)}{\Gamma(a \to \tau\tau)} = \frac{m_\mu^2 \sqrt{1-(2m_\mu/m_a)^2}}{m_\tau^2 \sqrt{1-(2m_\tau/m_a)^2}}.$$

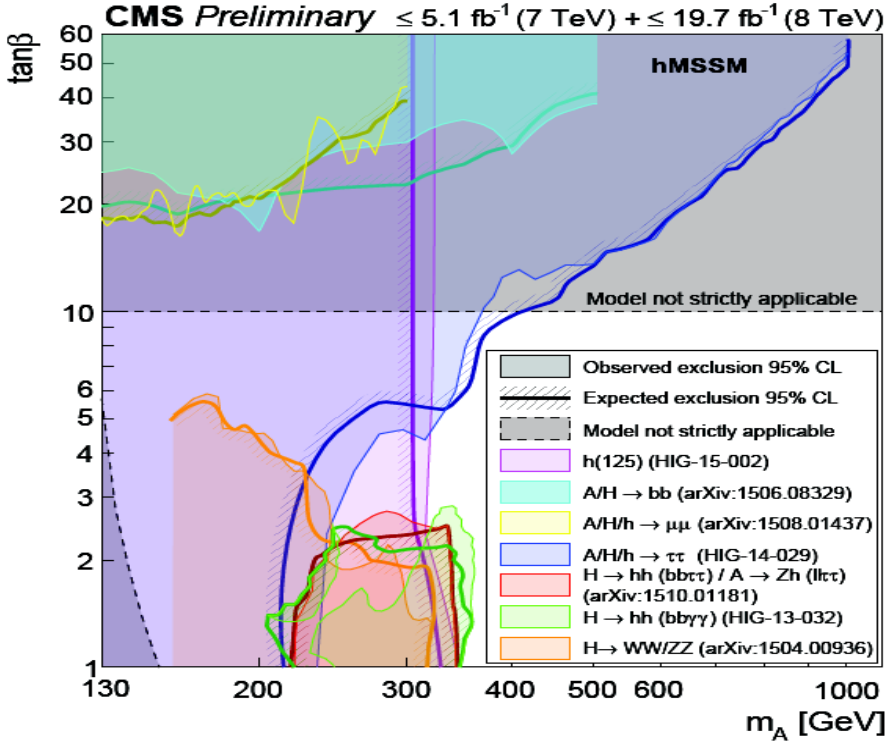


- Also such searches for a→γγ and a→bb̄

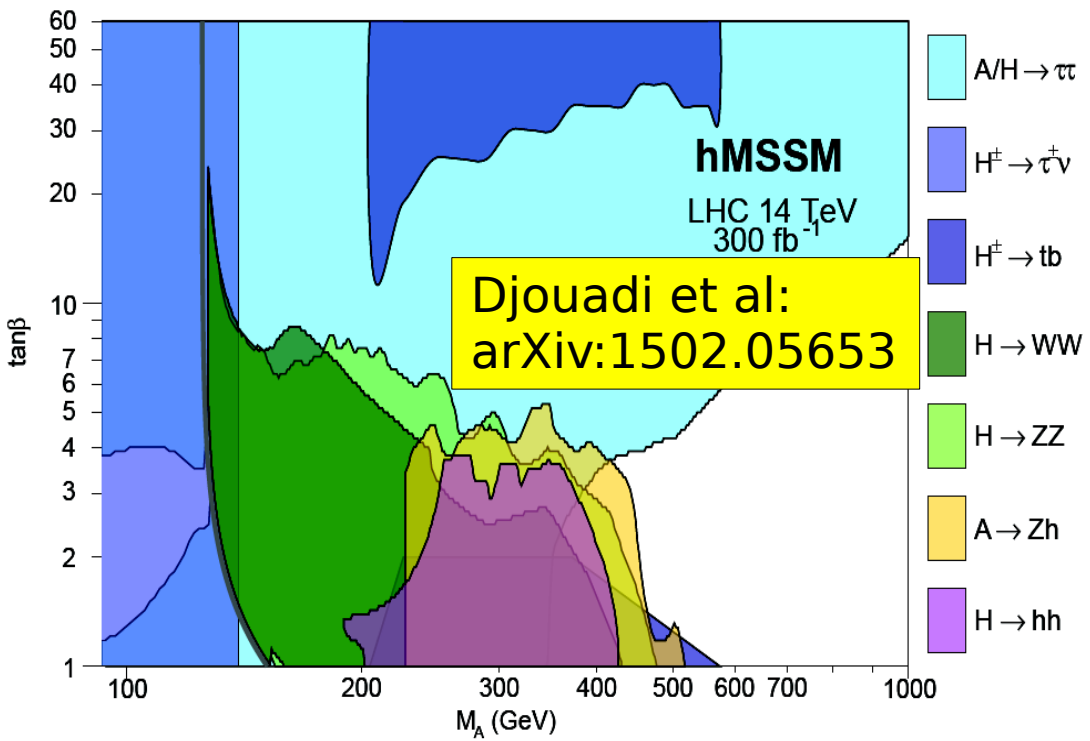
Summary

- Extensive searches for additional Higgs bosons consistent with MSSM and other 2HDM models
  - Good coverage at both large tanβ and low m_A
  - For low tanβ, little coverage in MSSM for $m_A > 2m_{top}$
- Run-2 searches need more luminosity for low m_A region
- Also many (CMS) searches for very light scalars

After Run-1



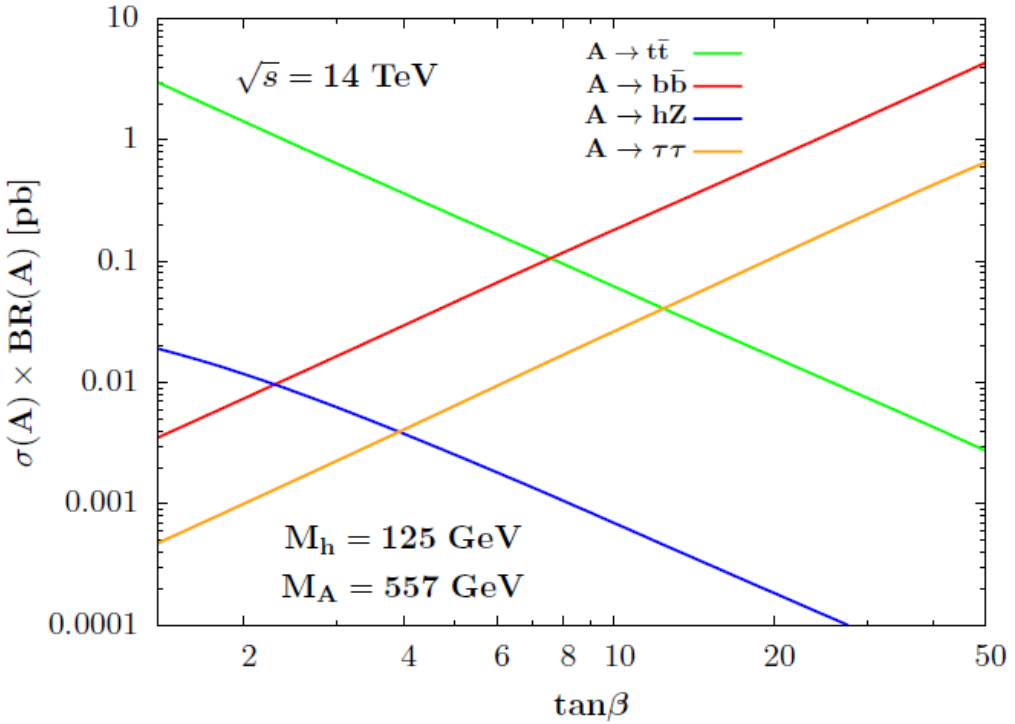
After Run-3?

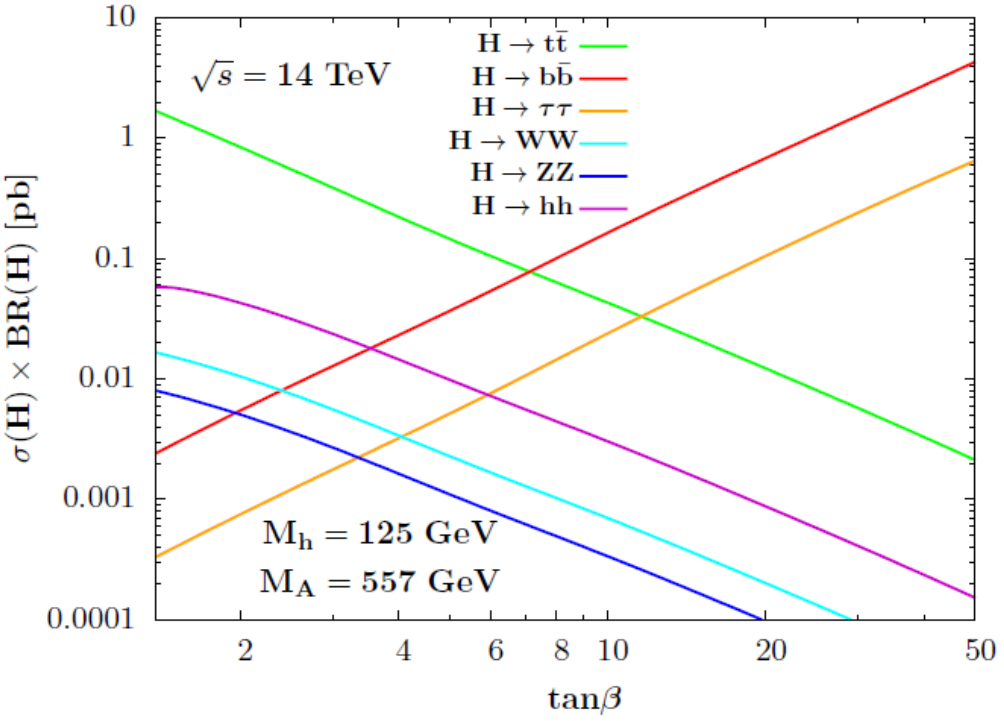


Backup

Heavy Higgs Boson Decays

Djouadi et al:
arXiv:1502.05653





m_h^{mod+} Scenario

m_h^{max} scenario modified to give right Higgs mass in most of m_A, tanβ plane

$\underline{m_h^{\text{mod+}}}$:

Carena et al: arXiv:1302.7033

$$
\begin{aligned}
m_t &= 173.2\ \text{GeV}, \\
M_{\text{SUSY}} &= 1000\ \text{GeV}, \\
\mu &= 200\ \text{GeV}, \\
M_2 &= 200\ \text{GeV}, \\
X_t^{\text{OS}} &= 1.5\, M_{\text{SUSY}}\ \text{(FD calculation)}, \\
X_t^{\overline{\text{MS}}} &= 1.6\, M_{\text{SUSY}}\ \text{(RG calculation)}, \\
A_b &= A_\tau = A_t, \\
m_{\tilde{g}} &= 1500\ \text{GeV}, \\
M_{\tilde{l}_3} &= 1000\ \text{GeV}\ .
\end{aligned}
$$