Searches for Heavy Higgs Boson(s)

Jianming Qian

University of Michigan

PITT PACC Workshop: Higgs and Beyond

December 3-5, 2015

Beyond the Standard Model

The Standard Model Higgs sector consists of one $SU(2)$ Higgs doublet field

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

Natural extensions to the SM Higgs sector:

- SM + a singlet S (real or complex);
- SM + an additional Higgs doublet, known as 2 Higgs doublet model (2HDM);
- 2HDM + a singlet S;
- Higgs triplet model; ......

Phenomenological and experimental consequences:

Non-SM-like Higgs bosons $\Rightarrow$ coupling modifications;

Additional neutral and/or charged Higgs bosons;

New production processes and decay modes; ....

SM + Singlet

The simplest extension of the standard model Higgs sector is the addition of a singlet S:

$$V(\phi,S)=\left\{\mu^2\phi^\dagger\phi+\lambda\left(\phi^\dagger\phi\right)^2\right\}+\left\{m_S^2S^2+\rho S^4\right\}+\kappa\left(\phi^\dagger\phi\right)S^2$$

Interesting phenomenology depends on whether $\langle S\rangle=0$.

If $\langle S\rangle\neq 0$, in general the singlet scalar and the "SM" Higgs boson can mix to form two mass eigenstates: $(h,\ H)$ assuming $h=h(125)$:

$$\begin{pmatrix} h \\ H \end{pmatrix}=\begin{pmatrix} \cos\theta & \sin\theta \\ \sin\theta & -\cos\theta \end{pmatrix}\begin{pmatrix} H_{SM} \\ S \end{pmatrix}$$

and new decay $H\to hh$ opens up if kinematically allowed.

The heavy Higgs has similar properties as the SM one with reduced production rate.

Constraints on the Heavy Higgs

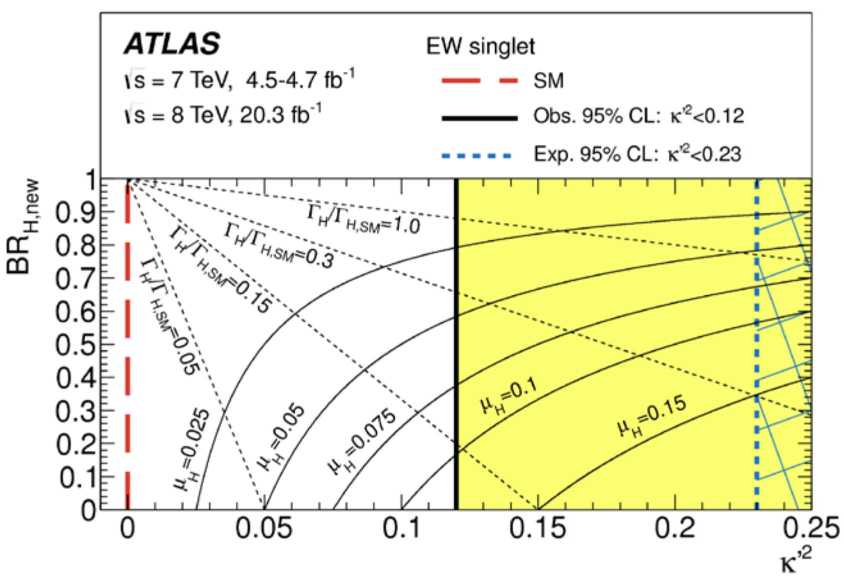
The mixing of H_{SM} and S leads to the modifications $\left(\kappa^2 = \cos^2\theta \text{ and } \kappa'^2 = \sin^2\theta\right)$

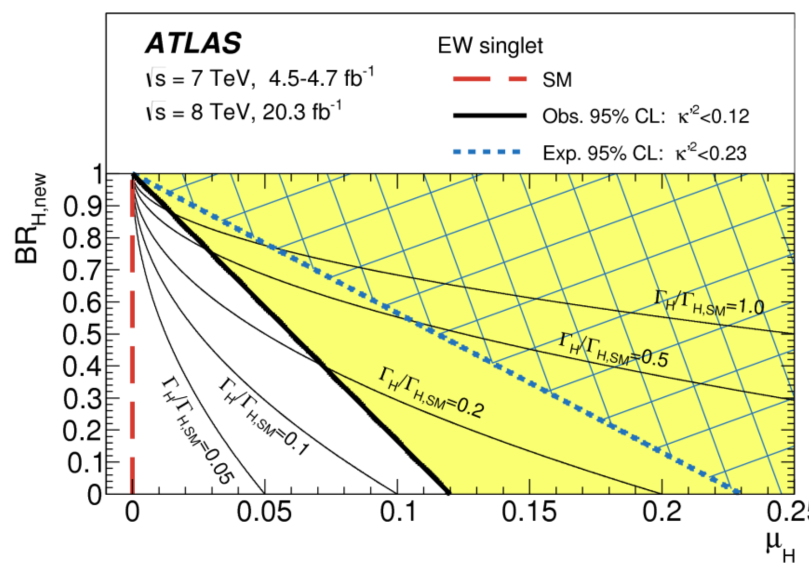
$$\sigma_h = \kappa^2 \times \sigma_h^{SM}, \qquad \Gamma_h = \kappa^2 \times \Gamma_h^{SM}, \qquad \mathrm{BR}_h = BR_h^{SM},$$

$$\sigma_H = \kappa'^2 \times \sigma_H^{SM}, \qquad \Gamma_H = \frac{\kappa'^2}{1 - BR_{new}} \times \Gamma_H^{SM}, \qquad \mathrm{BR}_H = \left(1 - BR_{new}\right) \times BR_H^{SM}$$

The measurement of the light Higgs boson can constrain the heavy Higgs boson:

$$\mu_h = \frac{(\sigma \times BR)_h}{(\sigma \times BR)_h^{SM}} = \kappa^2 \quad \Rightarrow \quad \mu_H = \frac{(\sigma \times BR)_H}{(\sigma \times BR)_H^{SM}} = \kappa'^2\left(1 - BR_{new}\right) = \left(1 - \mu_h\right)\left(1 - BR_{new}\right)$$





arXiv:1509.00672 independent of the mass of the heavy Higgs boson m_H.

2 Higgs Doublet Models (2HDM)

These models result in 5 Higgs bosons after the symmetry breaking:

- two neutral CP-even scalars: h and H;
- one neutral CP-odd pseudoscalar: A;
- two charged H^+ and H^- scalars.

and are described by 8 free parameters (2 in SM), often chosen to be

5 mass parameters: m_h, m_H, m_A, $m_{H^\pm}$ and m_{12}^2

2 angular parameters: α and $\tan\beta$

(One more parameter is fixed by W boson mass: $\upsilon = 246$ GeV)

α: mixing parameter of two CP-even Higgs scalars;

$\tan\beta = \frac{\upsilon_2}{\upsilon_1}$: ratio of V.E.V. of the two Higgs doublets

2HDMs are classified into 4 types according to Higgs-Fermion couplings

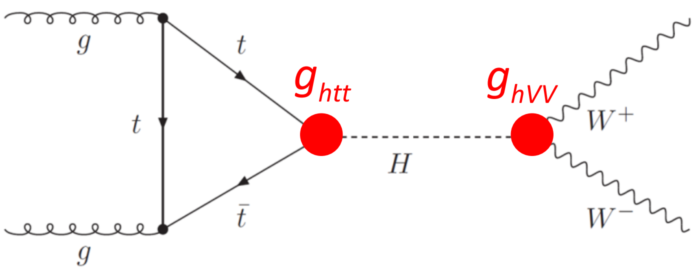
Type	I	II	III	IV
u	Φ_2	Φ_2	Φ_2	Φ_2
d	Φ_2	Φ_1	Φ_2	Φ_1
e	Φ_2	Φ_1	Φ_1	Φ_2
Also known as	"Fermiophobic"	MSSM-like	Lepton-specific	Flipped

Indirect Constraints from Coupling Fits

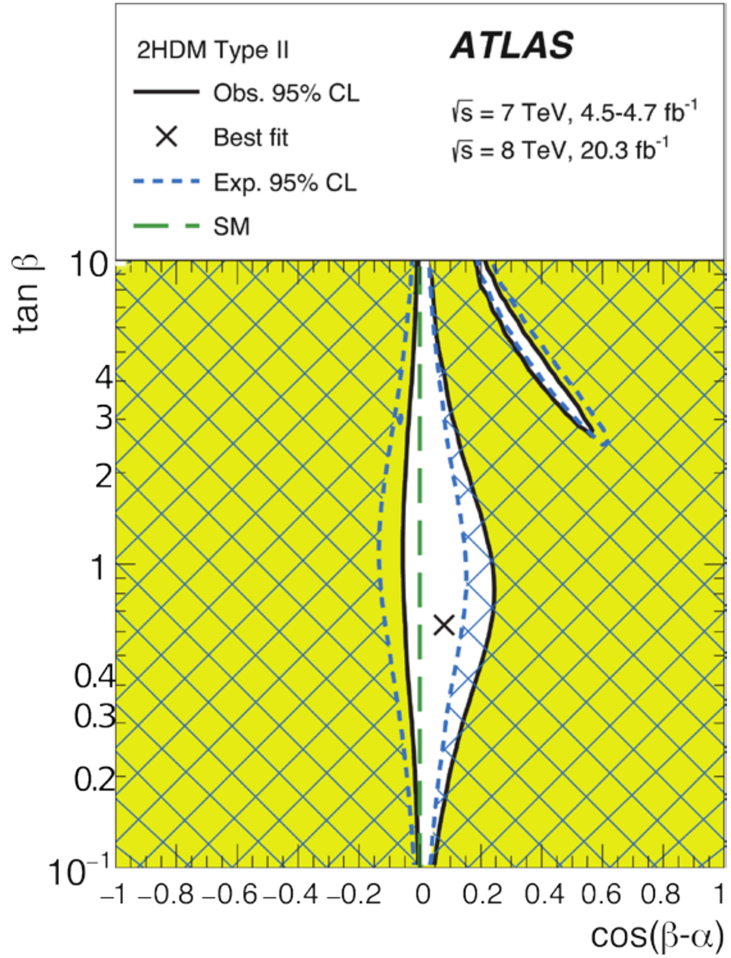
Assuming no change in Higgs decay kinematics and no new production process, the measured rates of $h(125)$ can be turned into constraints on the two 2HDM parameters: α and β

Parametrized using $\tan\beta$ and $\sin(\beta-\alpha)$

Vertex	Type II tree-level coupling factor
$h\,VV$	$\sin(\beta-\alpha)$
$h\,tt$	$\cos\alpha/\sin\beta = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)$
$h\,bb$	$-\sin\alpha/\cos\beta = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)$
$h\,\tau\tau$	$-\sin\alpha/\cos\beta = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)$



$$\frac{(\sigma\cdot BR)(gg\to H\to WW)}{\left[\sigma(gg\to H)\cdot BR(H\to WW)\right]_{SM}} \approx \left(\frac{g_{htt}}{g_{Htt}^{SM}}\right)^2 \times \left(\frac{g_{hVV}}{g_{hVV}^{SM}}\right)^2$$



Search for H→γγ

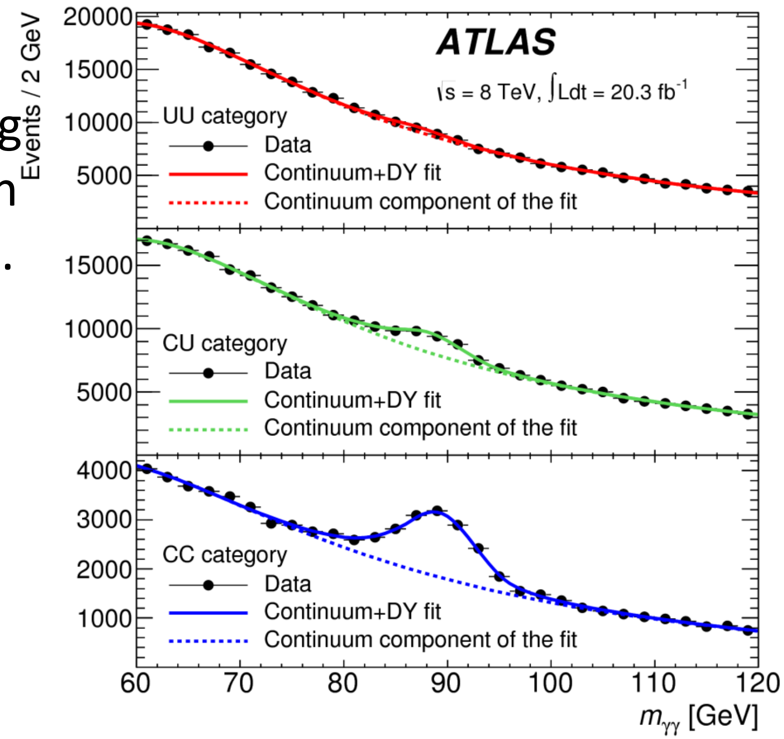
Categorized analysis for $65 < m_{\gamma\gamma} < 110$ GeV

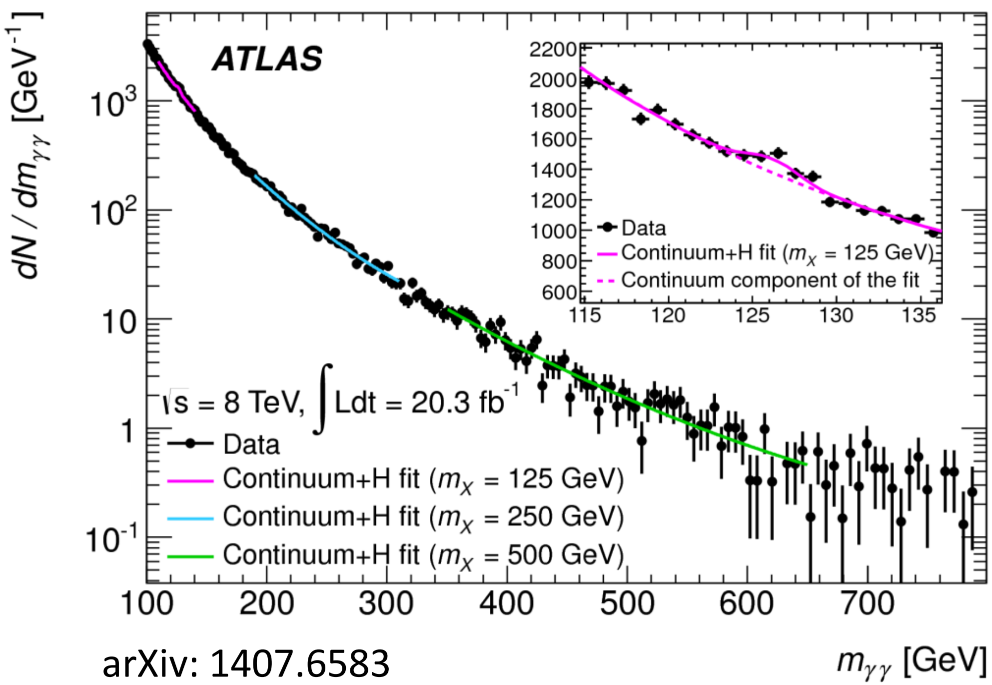
Look for resonance structures over smooth falling spectrum from QCD and Drell-Yan. Categorization to minimize the impact of Drell-Yan backgrounds.

UU (unconverted-unconverted)

UC (unconverted-converted)

CC (converted-converted)





arXiv: 1407.6583

Inclusive analysis for "high mass"

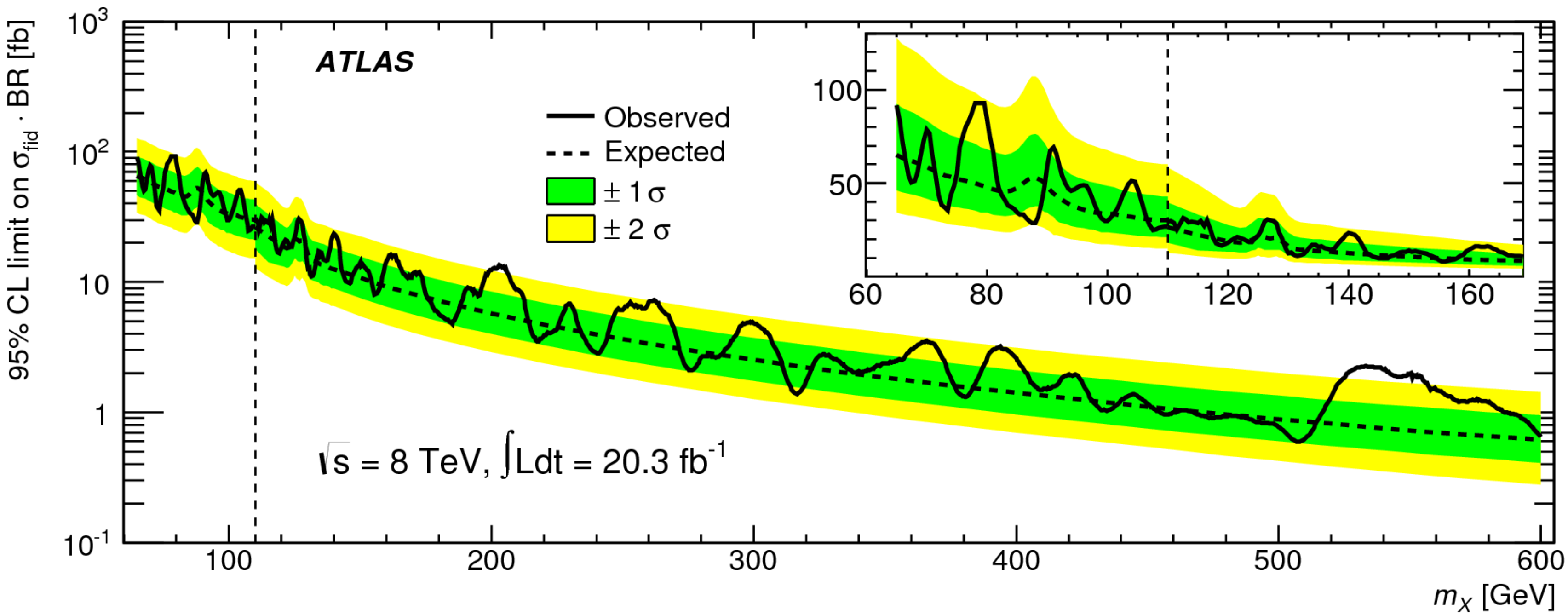
$110 < m_{\gamma\gamma} < 600$ GeV

Drell-Yan background less an issue

Search for H→γγ

Assuming narrow width for the signal: $\Gamma_H = 0.09 + 0.01 \times m_H$ GeV, fit the $m_{\gamma\gamma}$ distribution with background and signal models scaning the mass range 65-600 GeV, treating h(125) particle as background using the SM cross section for normalization.

Excellent mass resolution, particularly at high mass $\sim 1\%$.

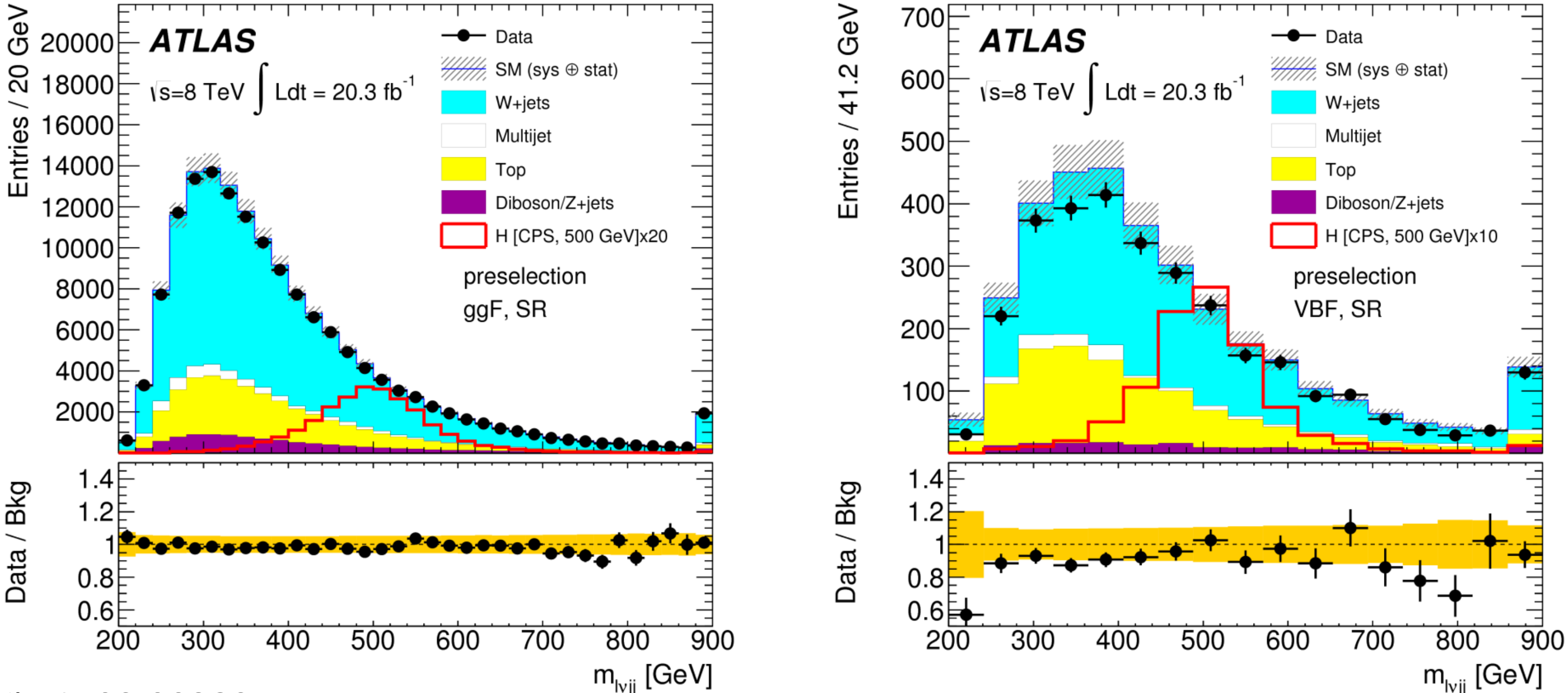


High Mass H→WW Search

Search for both narrow and "SM-like" resonances in the $H \rightarrow WW$ decay, two final states: 1) $WW \rightarrow \ell\nu\ell\nu$ and 2) $WW \rightarrow \ell\nu qq$

Consider both gluon-gluon fusion (ggF) and vector-boson fusion (VBF) production.

"SM-like" width scenario:
- $m_H < 400$ GeV, Breit-Wigner lineshape
- $m_H > 400$ GeV, Complex-pole scheme



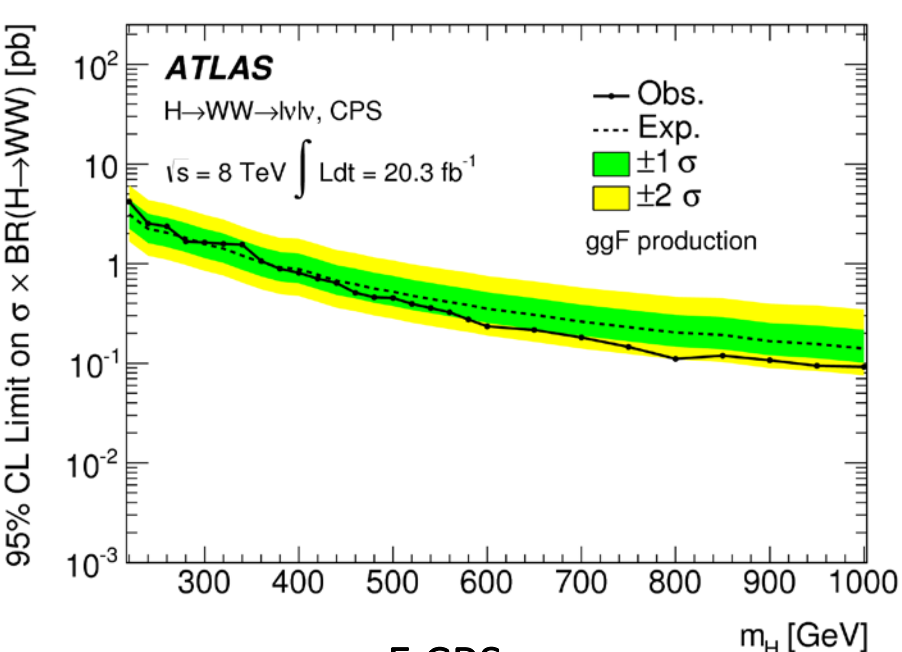
arXiv:1509.00389

High Mass H→WW Search

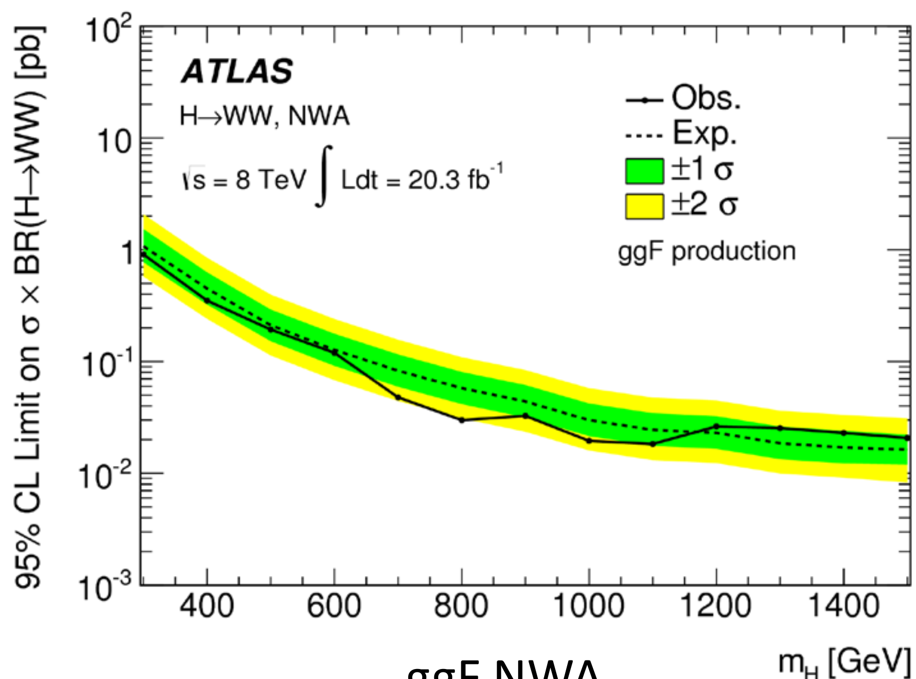
Typical mass resolution is about 15% for $\ell\nu\ell\nu$ and 5-10% for $\ell\nu qq$.

No significant excess above the expectation. Limits are set for both ggF and VBF production.

About a factor of two tighter limit for the NWA than the CPS scenarios. Similarly, the VBF limits are about a factor of two better than ggF.



ggF CPS



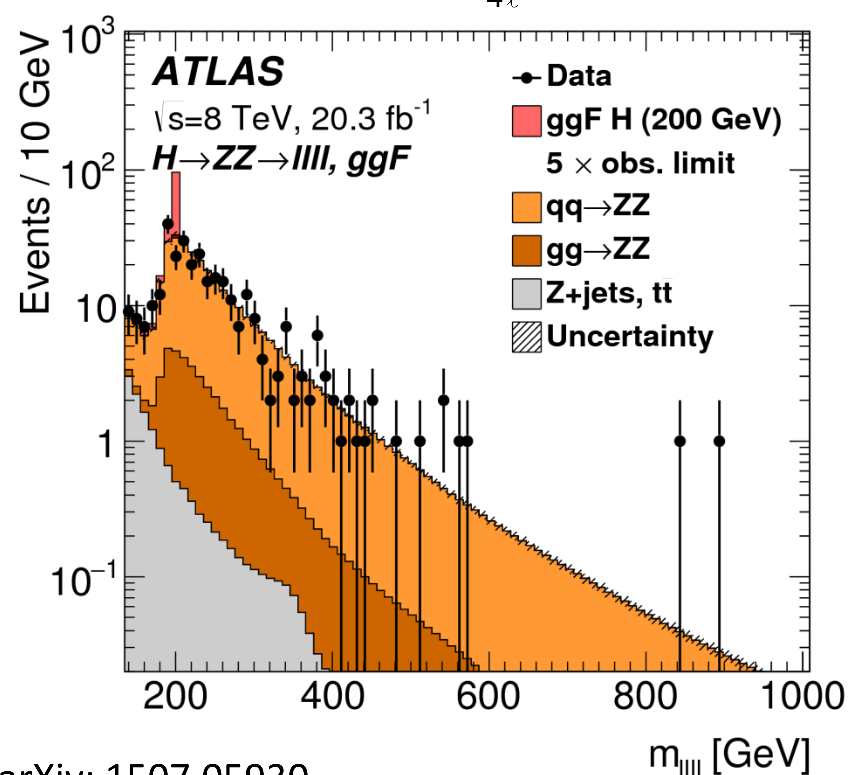
ggF NWA

High Mass H→ZZ Search

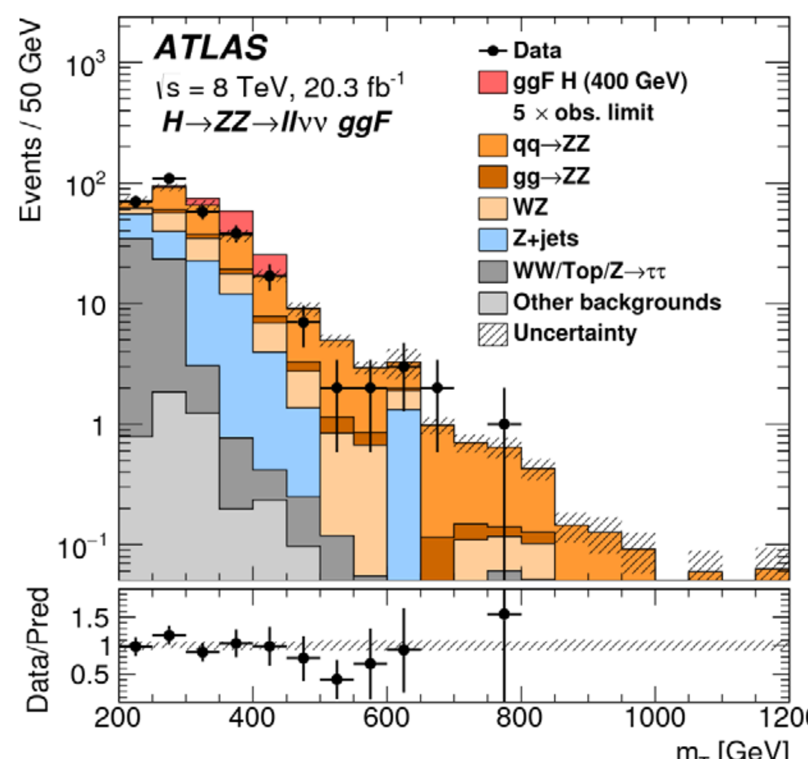
Search for a narrow resonance in the $H \to ZZ$ decay, four final states studied are: 1) $ZZ \to 4\ell$, 2) $ZZ \to \ell\ell\nu\nu$, 3) $ZZ \to \ell\ell qq$, 4) $ZZ \to \nu\nu qq$

Consider both ggF and VBF production, separate selection for events with ≥ 2 jets to target VBF production

$4\ell: \; m_{4\ell}$



$\ell\ell\nu\nu: \; m_T$

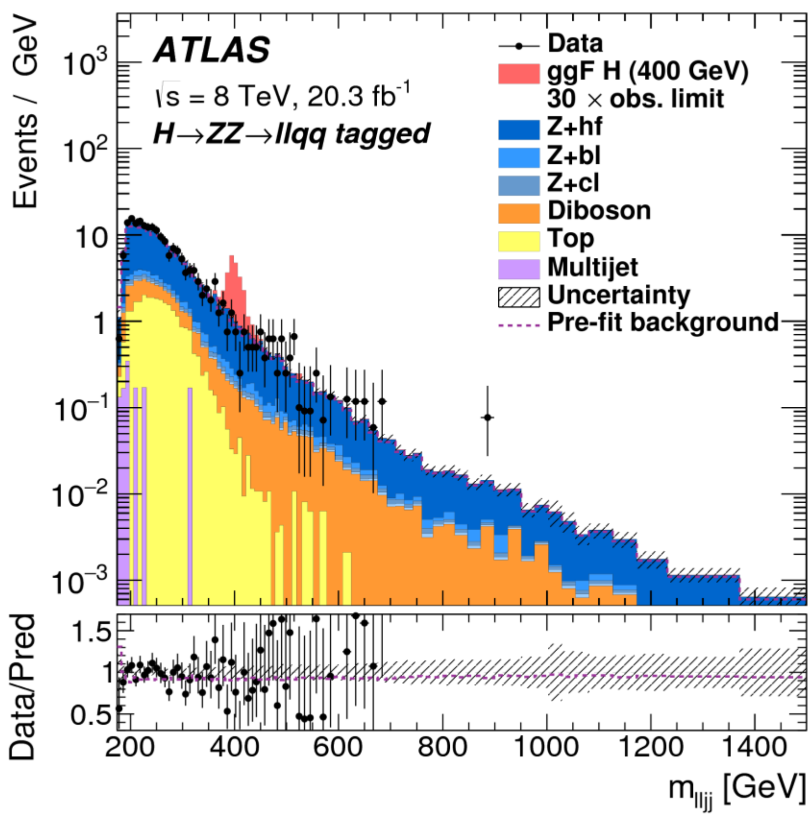


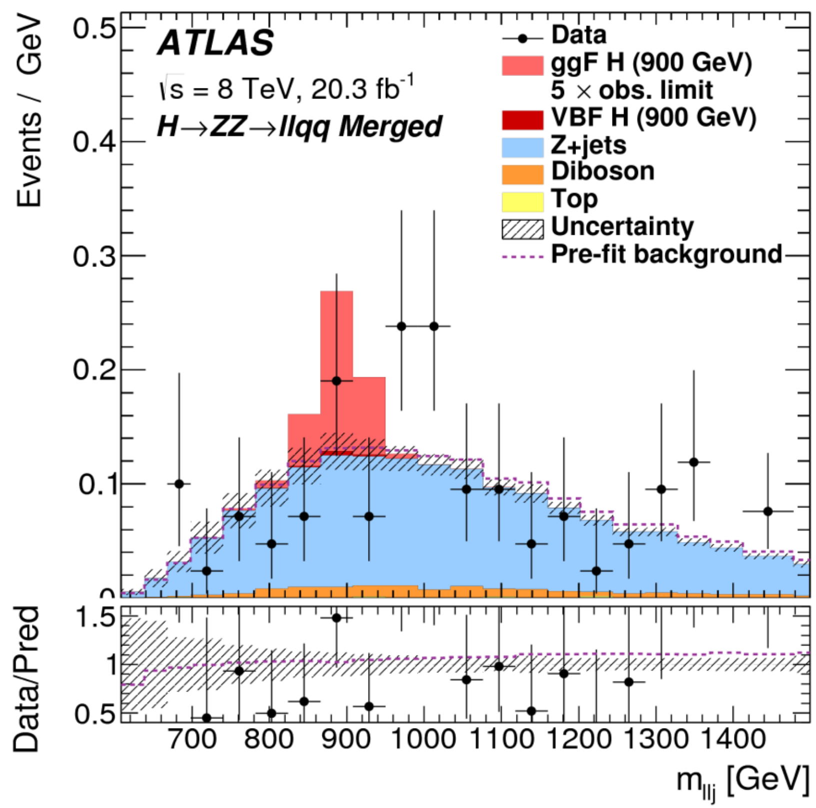
arXiv: 1507.05930

High Mass H→ZZ Search

At large Higgs boson mass, Z bosons have large momentum $\Rightarrow$ highly collimated Z decay products: merged jets. The sensitivities of resolved and merged analyses cross over around 1 TeV.

For ZZ $\rightarrow \ell\ell$qq, include merged analysis for $m_H > 600$ GeV.

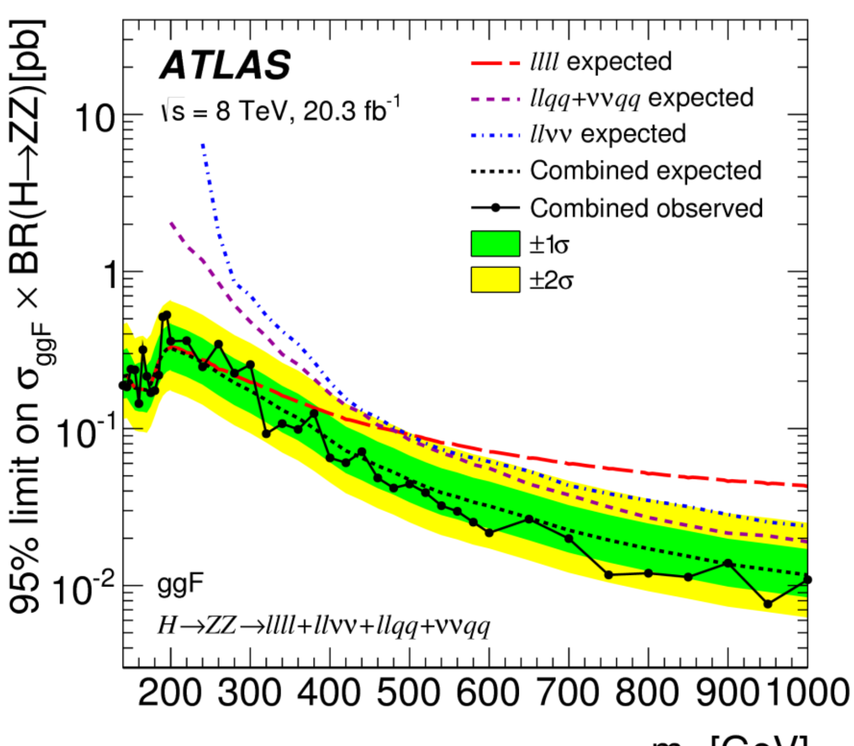




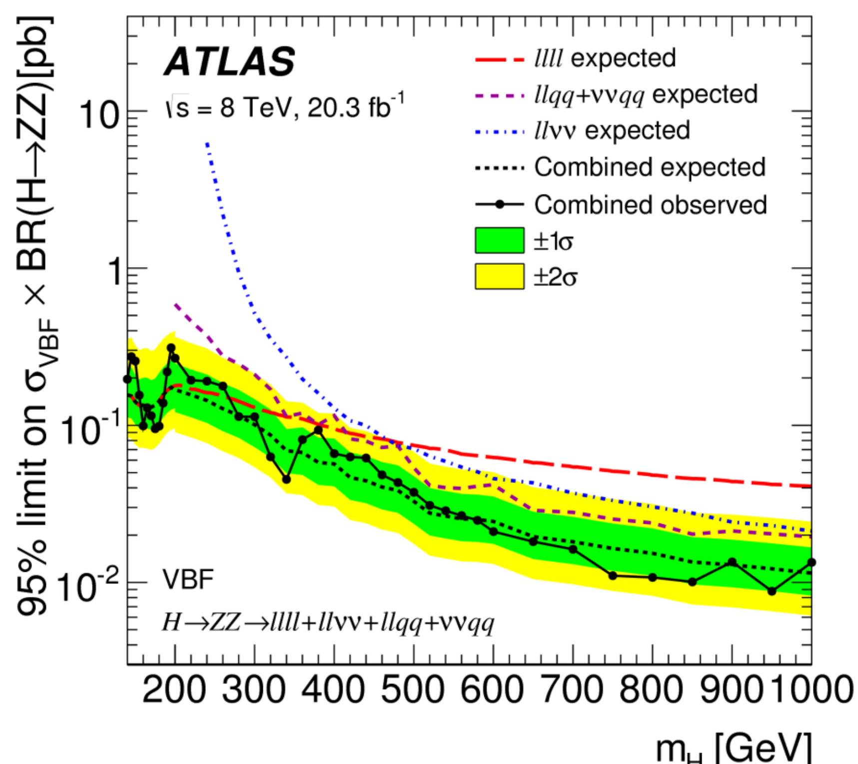
High Mass H→ZZ Search

Mass resolution is typically a few percent for 4ℓ and $\ell\ell$qq final states and 10-20% for $\ell\ell\nu\nu$ and $\nu\nu$qq final states.

No significant excesses, combining the results from all analyses and setting limit on $\sigma \times$BR for both ggF and VBF production



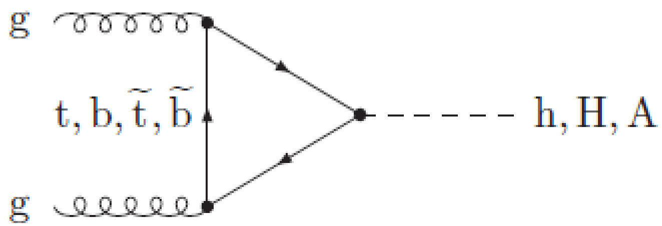
ggF



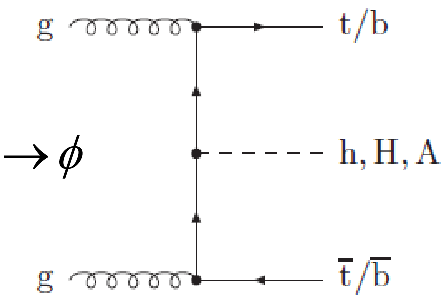
VBF

MSSM Heavy Neutral Higgs Boson

$gg \to \phi$



$bb \to \phi$



$\phi = A,\ H;\quad g_{\phi bb} \propto \tan\beta,\ \ g_{\phi tt} \propto \cot\beta$

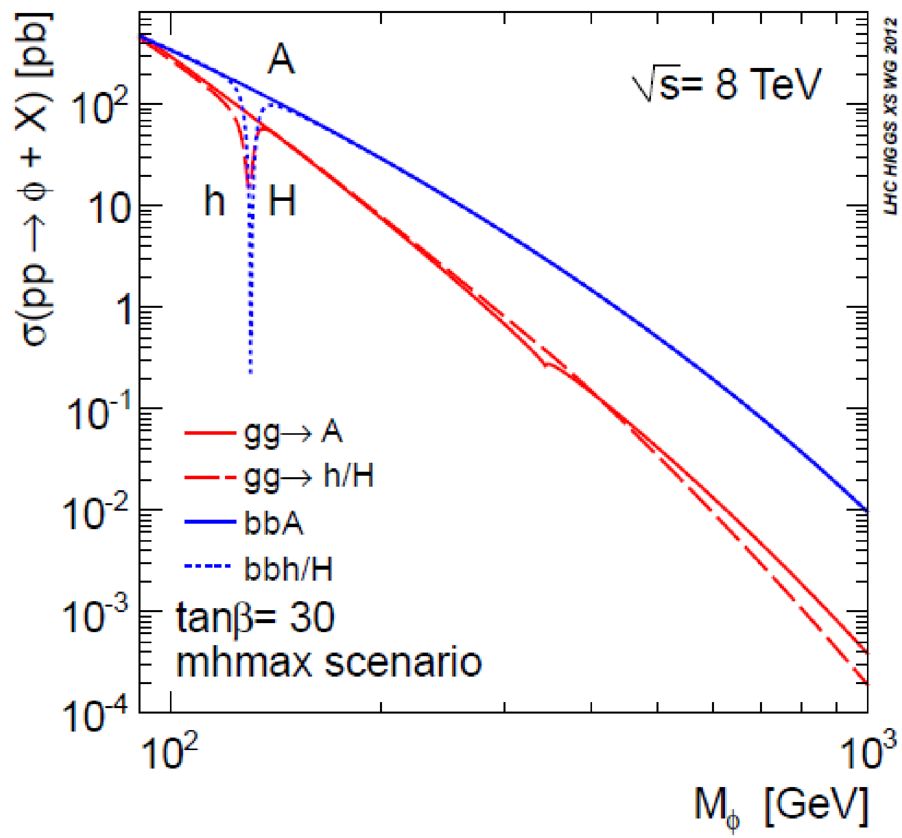
Again two main production processes:

$gg \to \phi$ dominates for $\tan\beta \sim 1$

$bb \to \phi$ dominates for $\tan\beta \gg 1$

The heavy CP-even Higgs boson *H* has similar decay modes as the SM Higgs boson with modified branching ratios

The CP-odd Higgs boson *A* has no *AVV* coupling at tree-level, thus decays to fermion pairs primarily.



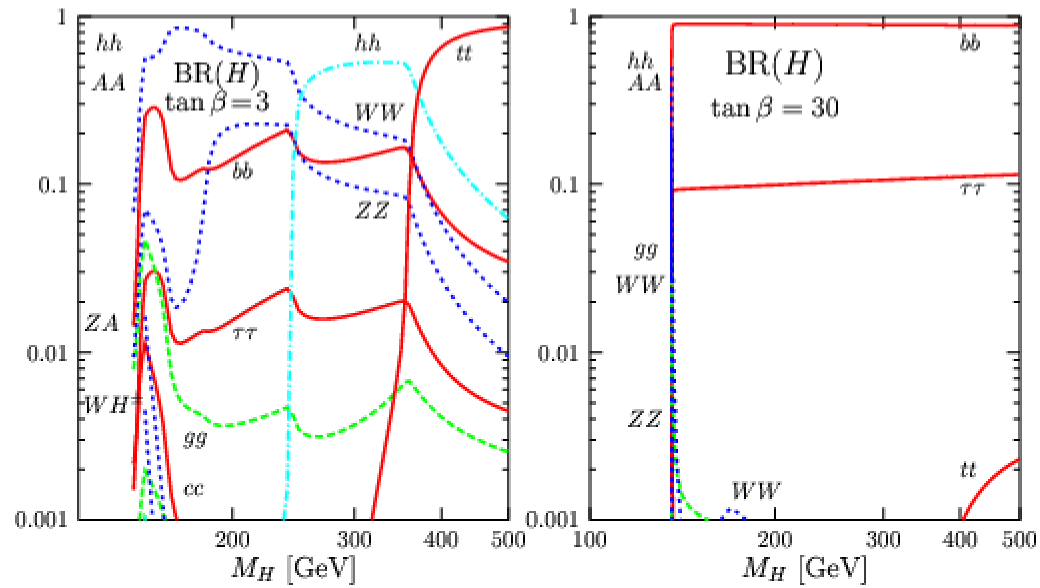
MSSM Heavy Neutral Higgs Boson

At $\tan\beta \gg 1$, $\phi(H,A) \to \tau\tau$ and bb decays dominate:

$BR(\phi \to bb) \sim 90\%$,

$BR(\phi \to \tau\tau) \sim 10\%$

Djouadi *et al.* arXiv:0901.2030



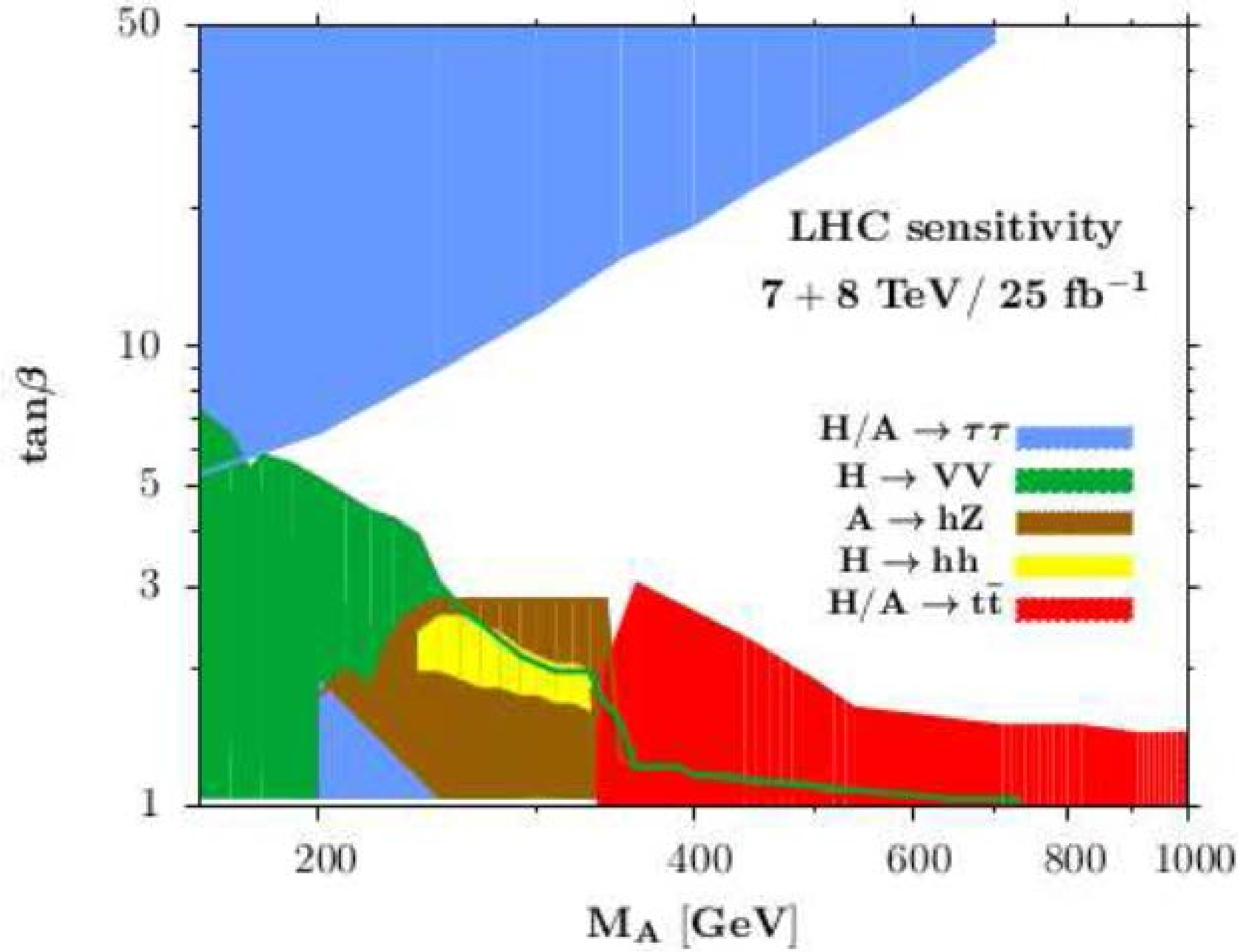
With a leptonic signature, $\phi \to bb$ search is difficult, particularly at low ϕ mass.

$\phi \to \tau\tau$ search has been the focus at the LHC. Keys to the search:

- identification of τ leptons through $\tau \to e/\mu + \nu's$ and $\tau \to h + \nu's$ decays
- reconstruction of the $\tau\tau$ invariant mass using methods such as missing mass calculator (MMC). Typical resolution $\sigma(m_{\tau\tau})/m_{\tau\tau} \sim 10-20\%$

MSSM Parameter Coverage

An illustration…



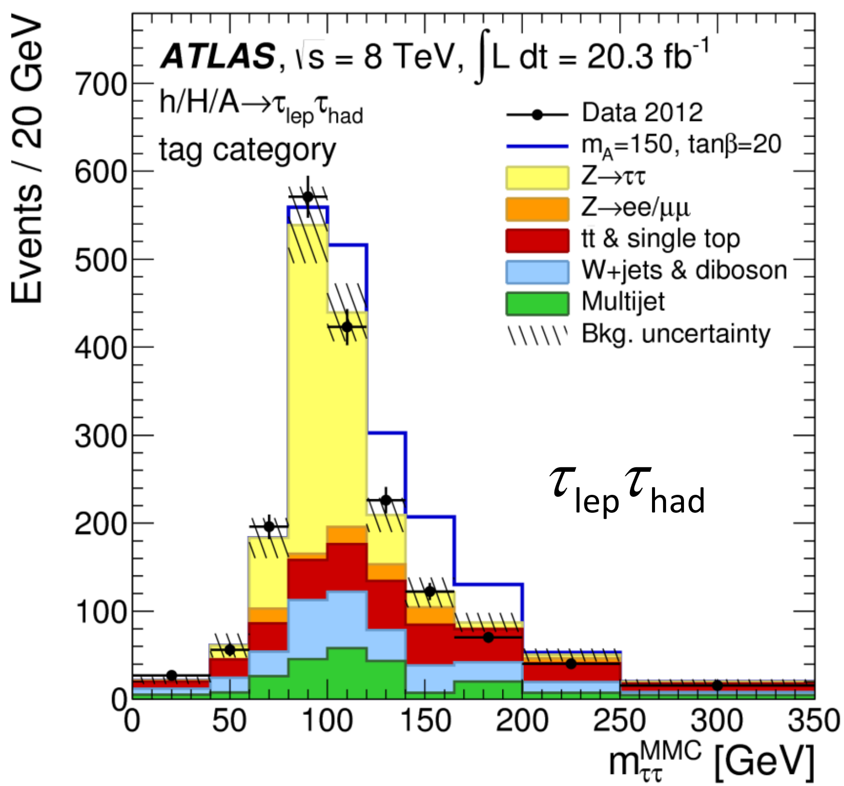
Djouadi, arXiv:1311.0720

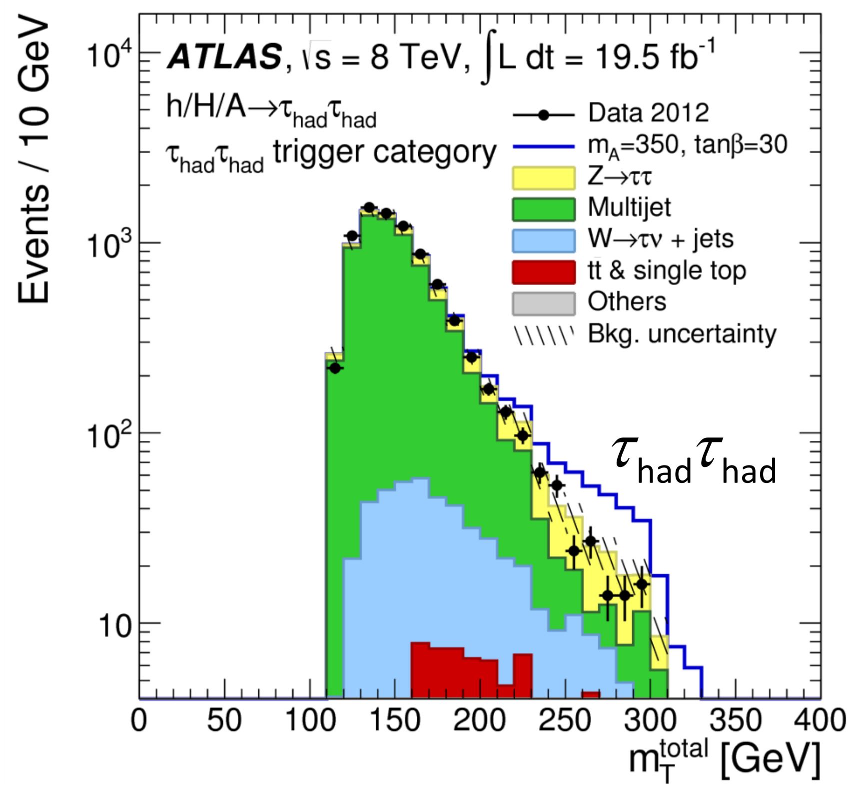
H/A→ττ

Three $\tau\tau$ decay final states: $\tau_{\text{lep}}\tau_{\text{lep}}\,(e\mu)$, $\tau_{\text{lep}}\tau_{\text{had}}$, $\tau_{\text{had}}\tau_{\text{had}}$

Low mass $(<200\text{ GeV})$: $\tau_{\text{lep}}\tau_{\text{lep}}$, $\tau_{\text{lep}}\tau_{\text{had}}$; b-tagged and veto

High mass $(>200\text{ GeV})$: $\tau_{\text{lep}}\tau_{\text{had}}$, $\tau_{\text{had}}\tau_{\text{had}}$

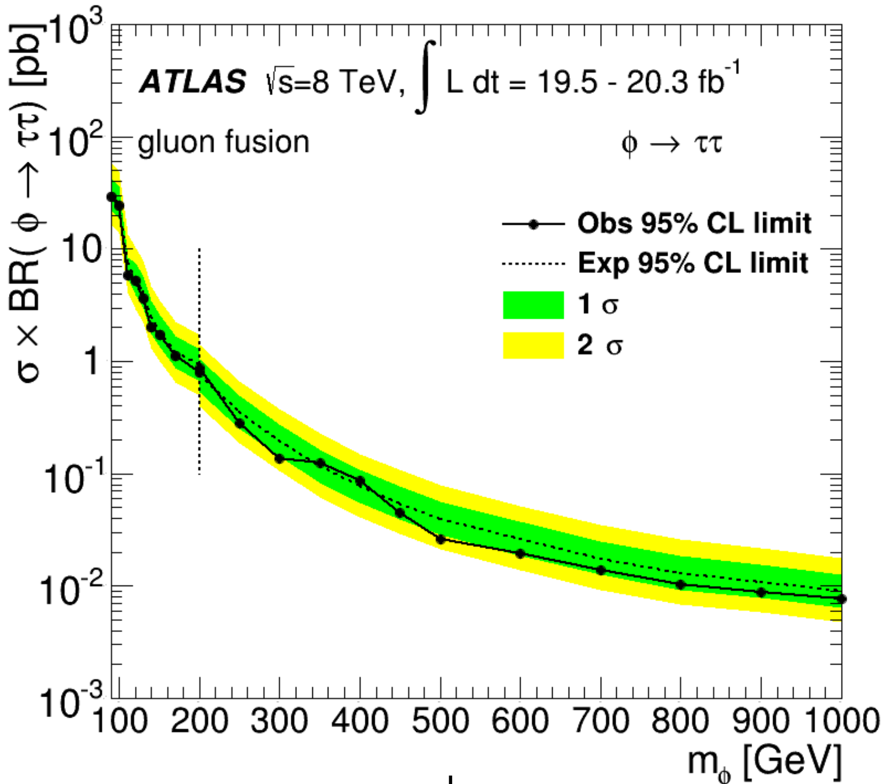




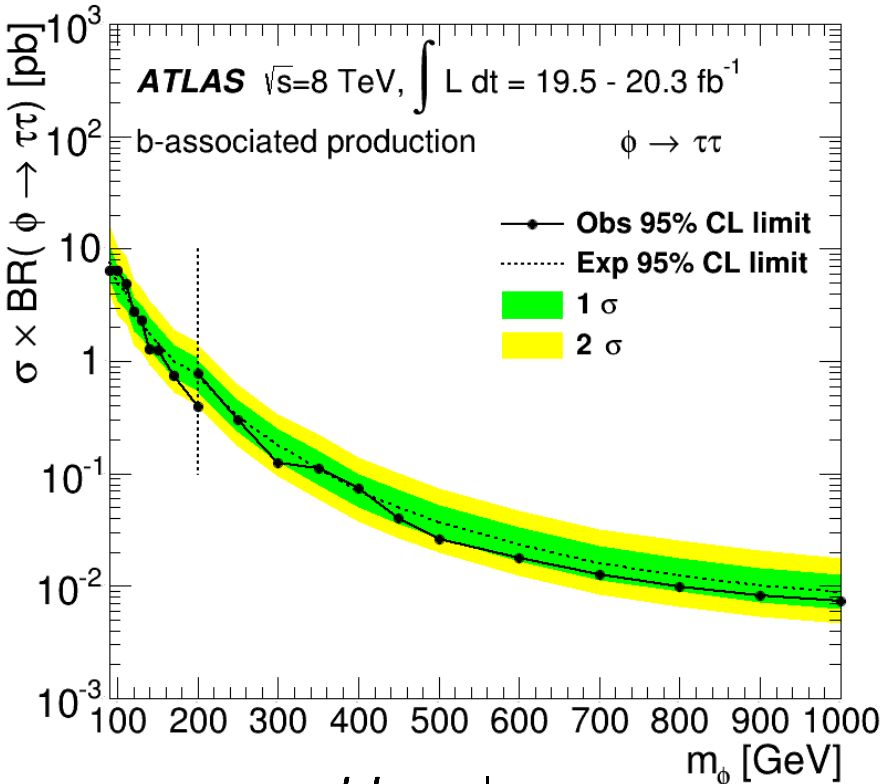
arXiv: 1409.6064

H/A→ττ

No significant excess is observed, set limits on cross sections for both gluon fusion and b-quark associated production



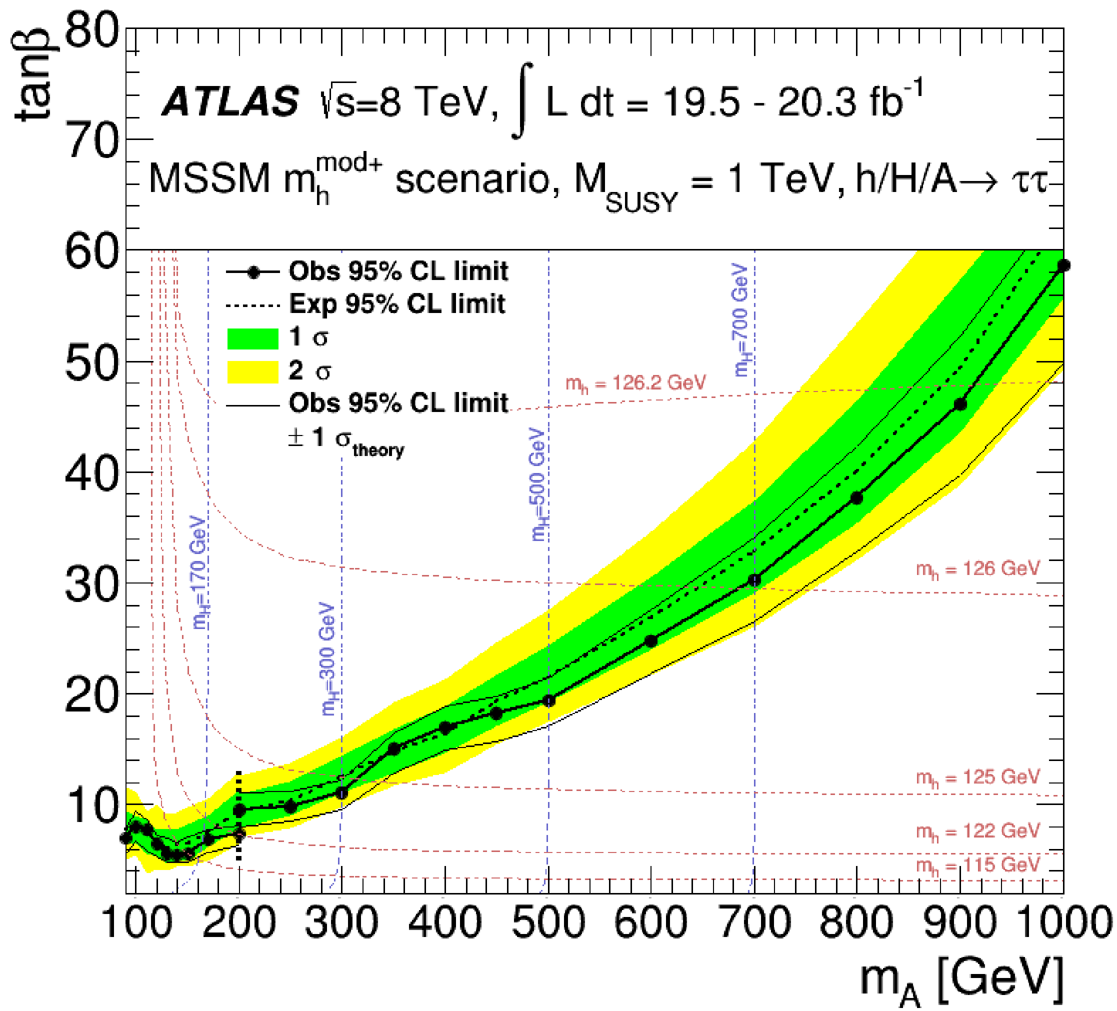
$gg \to \phi$



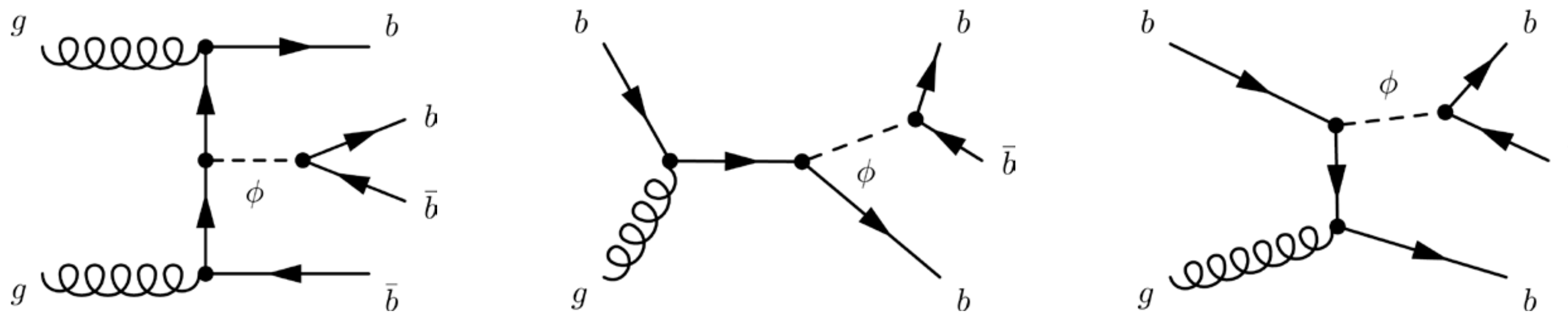
$bb \to \phi$

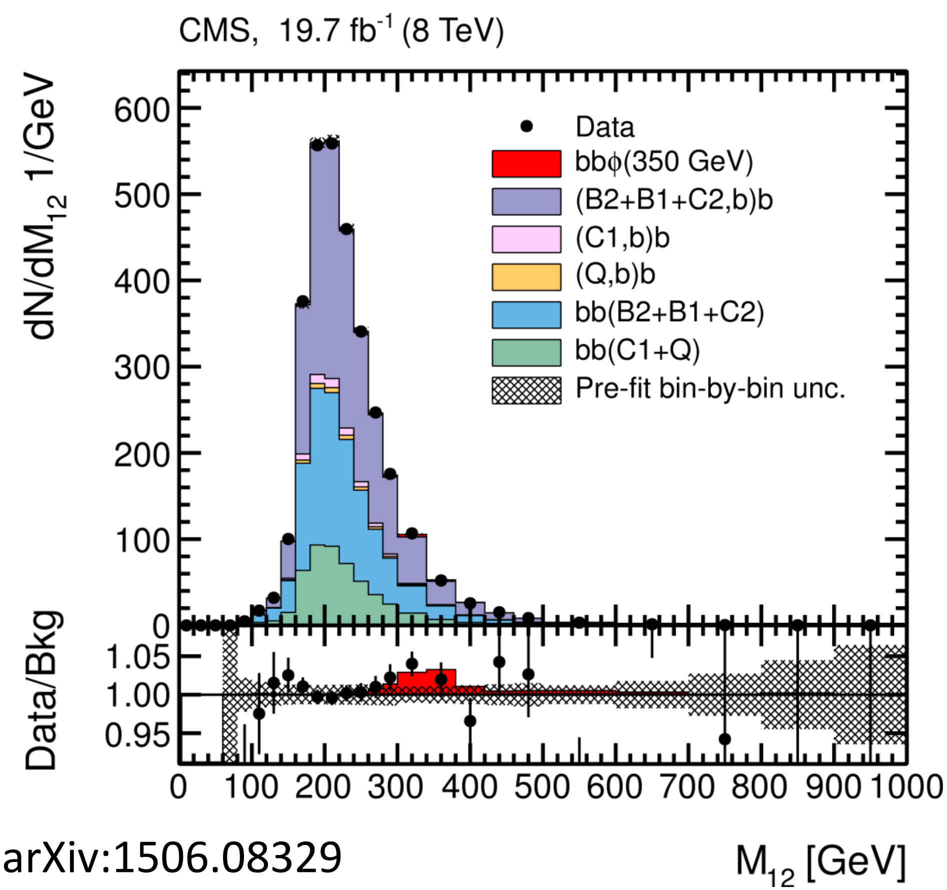
H/A→ττ

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



Search for H/A→bb





arXiv:1506.08329

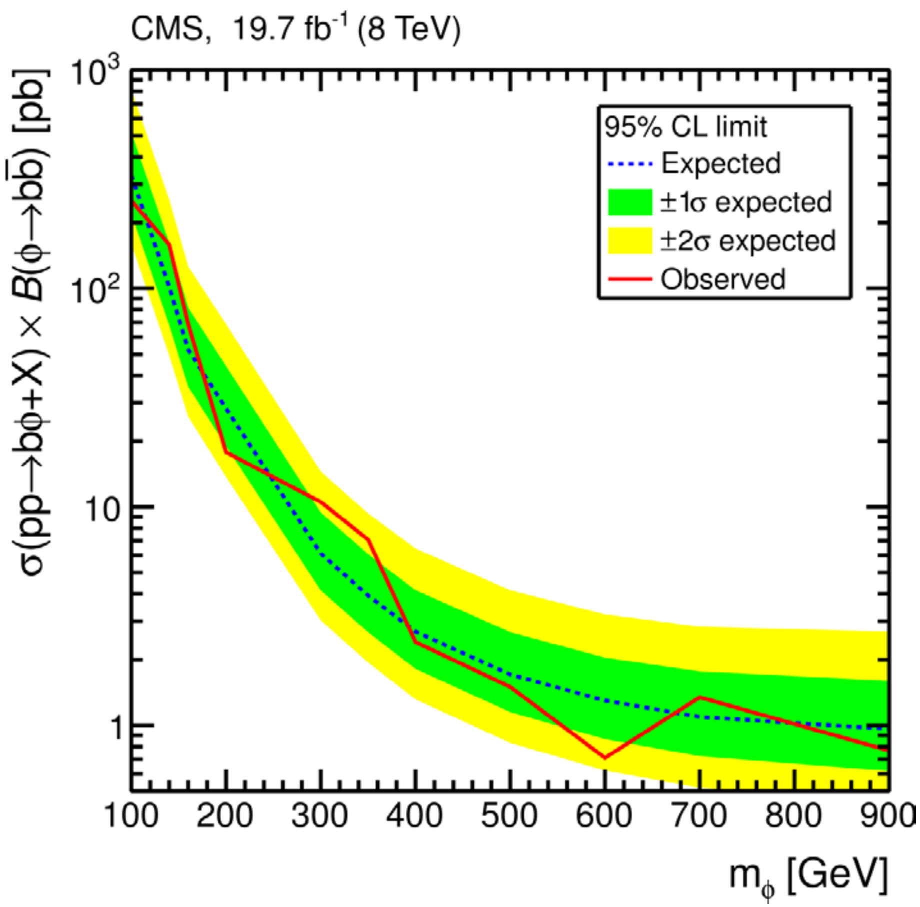
$H/A \to bb$ has the largest branching ratio $\sim$90% at large tanβ, but suffers from large QCD background.

However, it has good sensitivity at high mass where QCD jet production is significantly reduced.

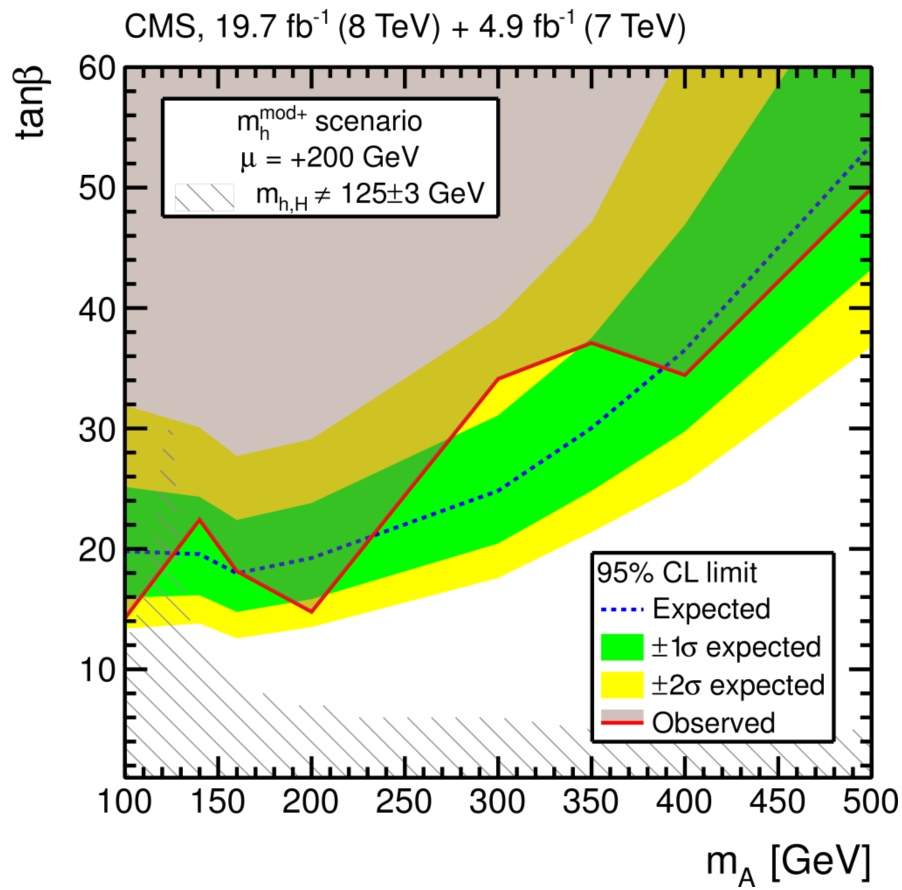
Search for events with 2 or 3 b-tagged high pT jets

Search for H/A→bb

Cross section limit



Exclusion region



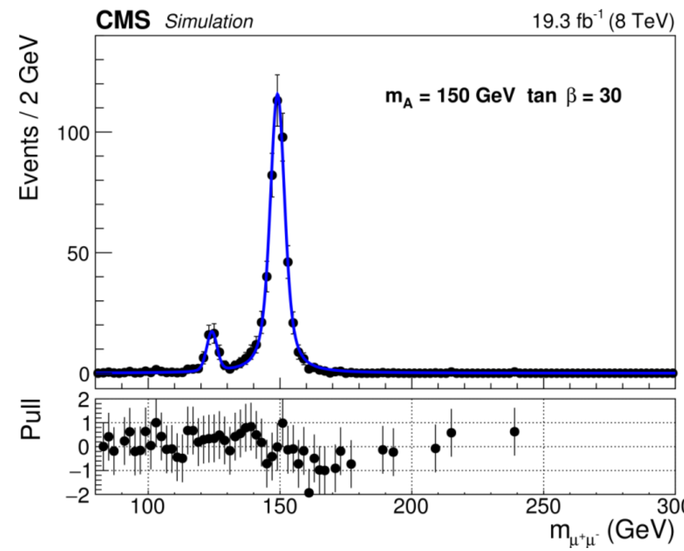
Not competitive as the search in H/A $\rightarrow \tau\tau$

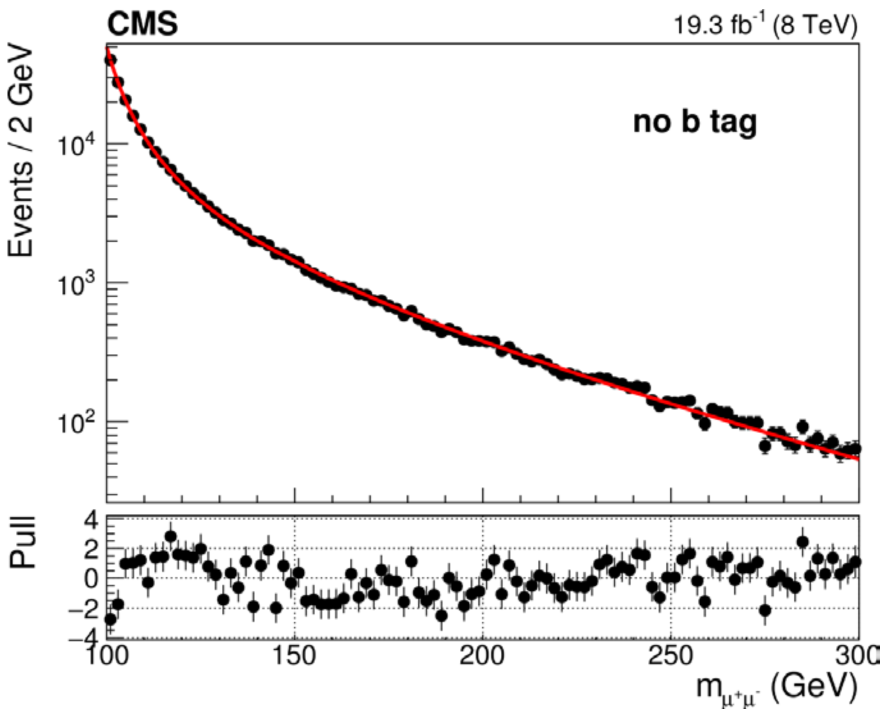
Search for H→μμ

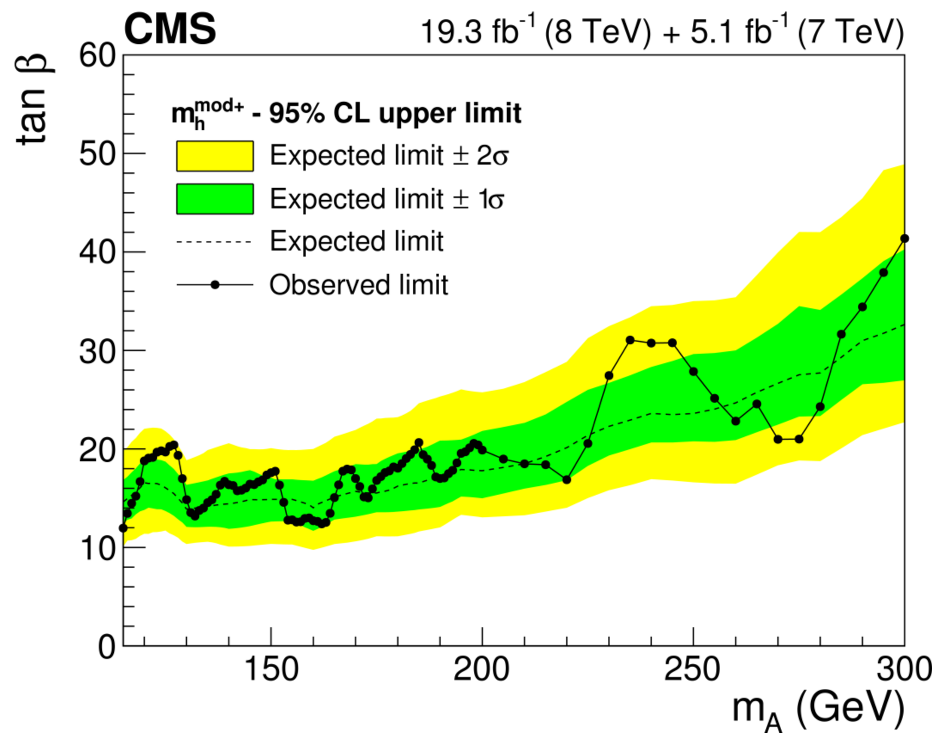
Low rate and huge background, but clean events and good mass resolution!

Search for resonance structures over the smooth Drell-Yan backgrounds in

- untagged (gluon-gluon fusion production)
- tagged (associated production)







arXiv:1508.01437

Search for A→Zh→$\ell\ell\tau\tau$

assuming h=h(125)

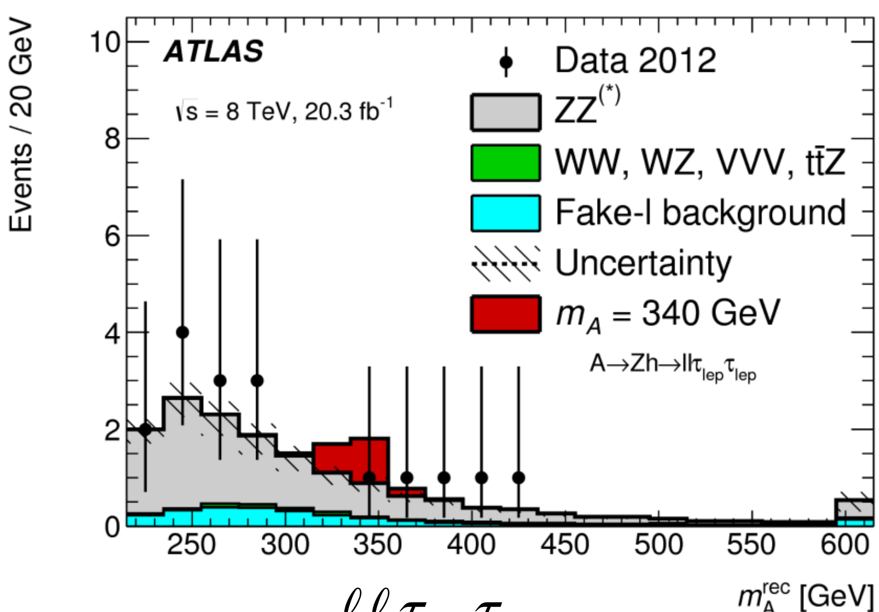
Three $\tau\tau$ decay final states: $\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$

Two leptons from $Z \to ee$ or $\mu\mu$ decays,

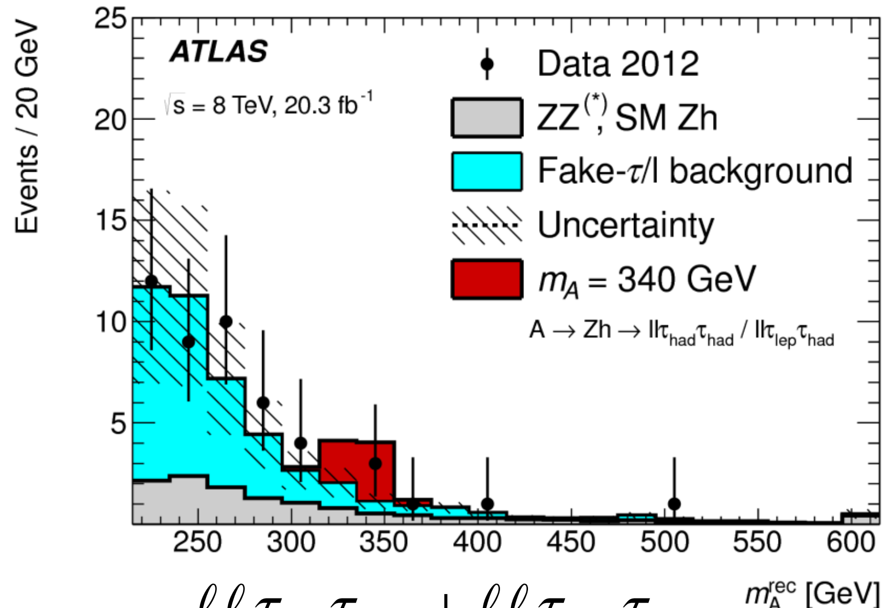
Estimate $m_{\tau\tau}$ using Missing Mass Calculator, calculate m_A

$$m_A^{rec} = m_{\ell\ell\tau\tau} + (m_Z - m_{\ell\ell}) + (m_h - m_{\tau\tau})$$

Resolution varies between 3-5% for m_A between 220-1000 GeV



$\ell\ell\tau_{lep}\tau_{lep}$



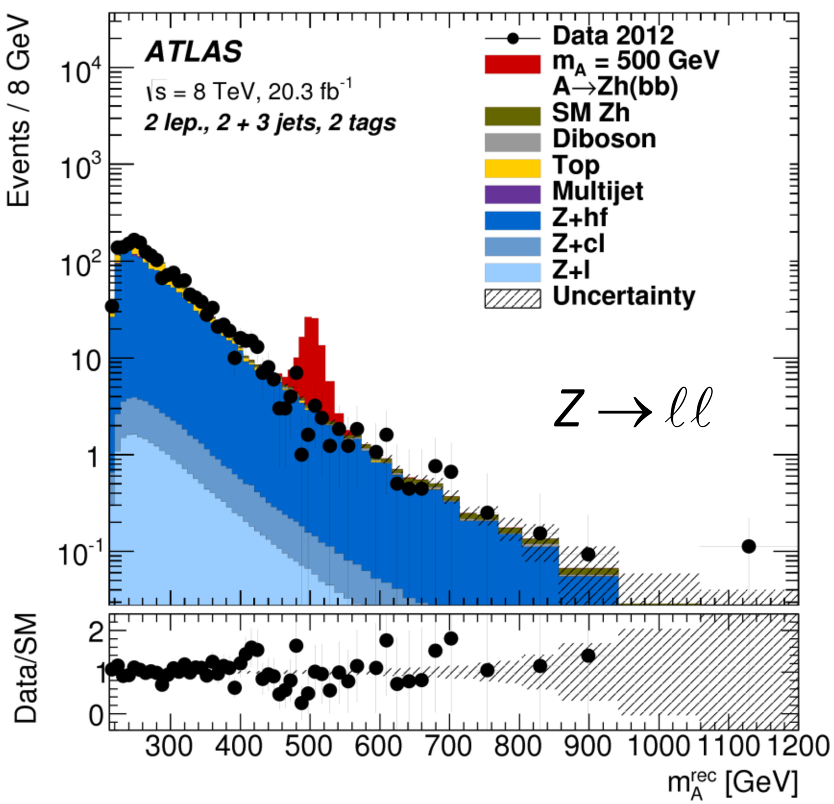
$\ell\ell\tau_{lep}\tau_{had} + \ell\ell\tau_{had}\tau_{had}$

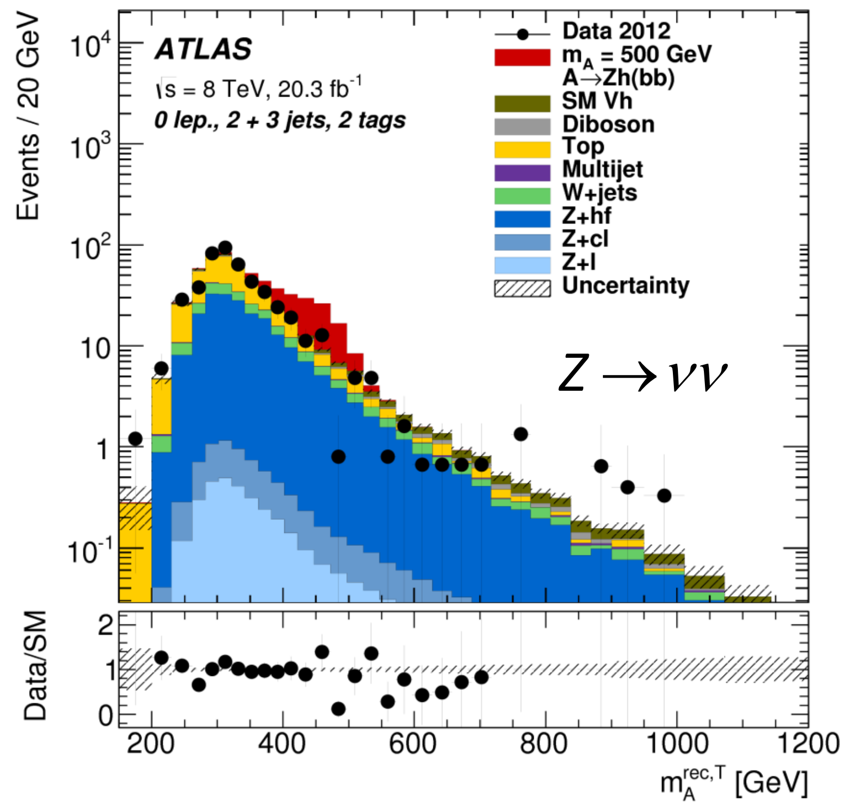
arXiv:1502.04478

Search for A→Zh→ℓℓbb,νν bb

Two b-tagged jets with $p_T > 45(20)$ GeV and $105 < m_{bb} < 145$ GeV, rescale m_{bb} to m_h, mass resolution 2-3% in the $\ell\ell bb$ final state

The $\nu\nu$bb final state is selected with large $E_T^{miss} > 120$ GeV and uses transverse mass as the discriminant

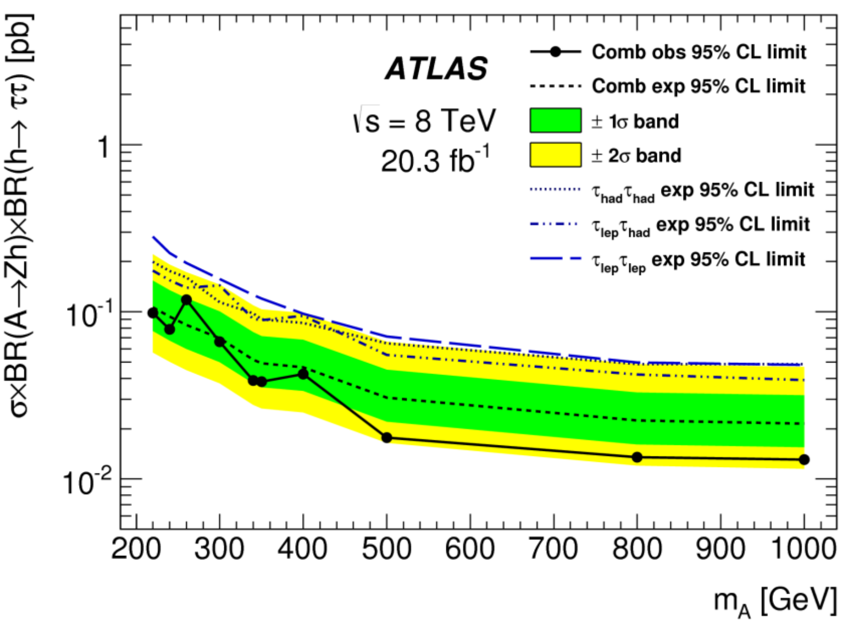




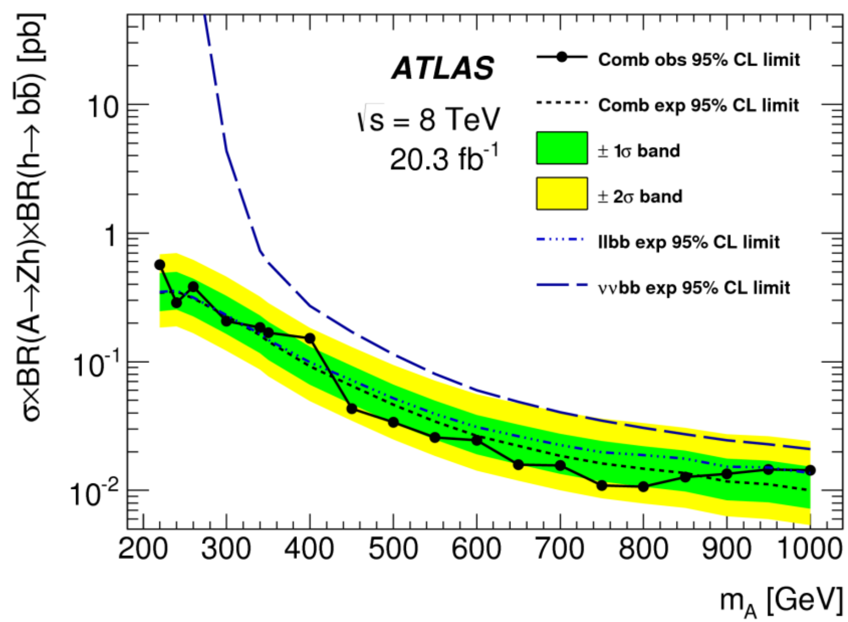
Search for A→Zh

No evidence for the production of A boson is observed

Separate limits for $h \rightarrow bb$ and $h \rightarrow \tau\tau$ decays as their branching ratios in BSM models may be different from the SM values



$h \rightarrow \tau\tau$

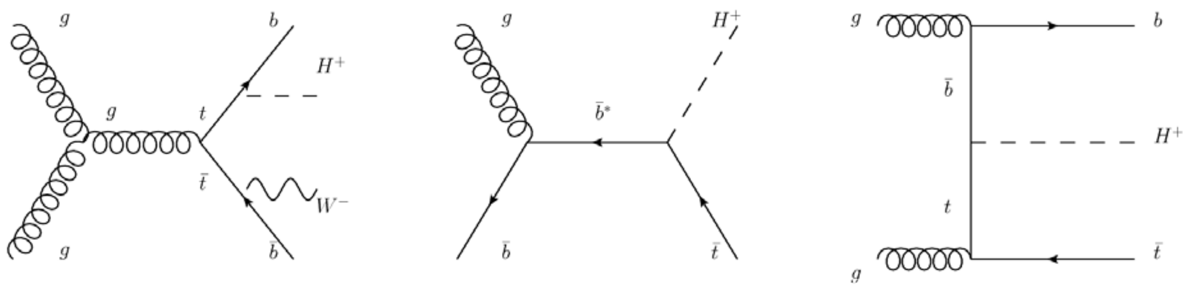


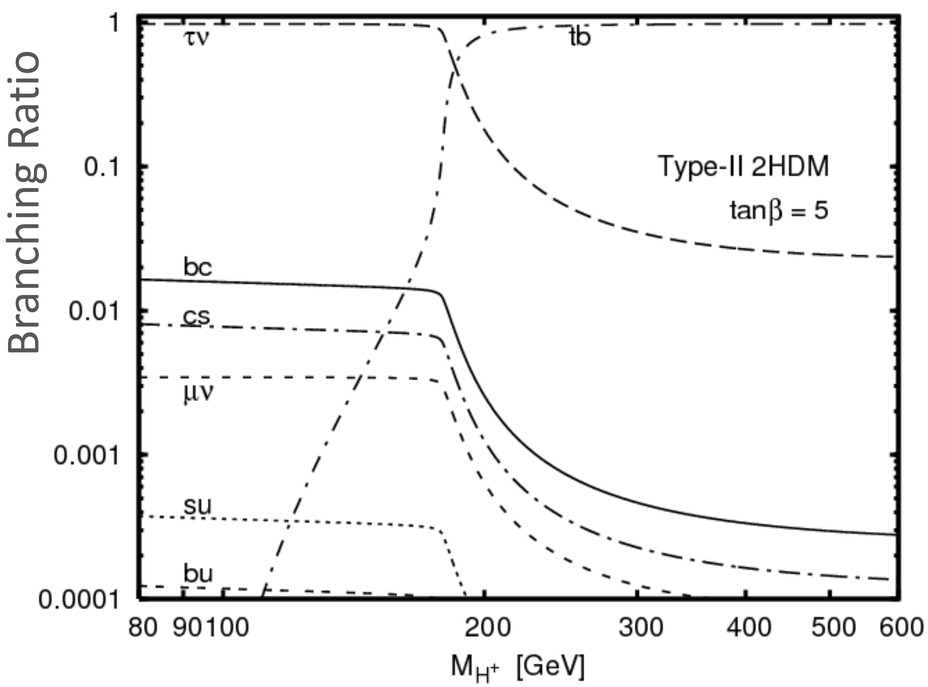
$h \rightarrow bb$

Charged Higgs Boson

Two main production processes at the LHC:

- light H$^{\pm}$ $(m_{H^{\pm}} < m_t - m_b)$: from top quark decay $t \to H^{+}b$;
- heavy H$^{\pm}$ $(m_{H^{\pm}} > m_t)$: in association with the top quark $tH^{+}(b)$





Similarly, two dominant decay modes depending on the mass. In much of the parameter space:

Light $H^{\pm}$ $(m_{H^{\pm}} < m_t)$:

$\mathrm{BR}\left(H^{\pm} \to \tau\nu\right) \sim 100\%$

Heavy $H^{\pm}$ $(m_{H^{\pm}} > m_t + m_b)$:

$\mathrm{BR}\left(H^{\pm} \to tb\right) \sim 90\%$

$\mathrm{BR}\left(H^{\pm} \to \tau\nu\right) \sim 10\%$

Charged Higgs Boson

Two major search signatures:

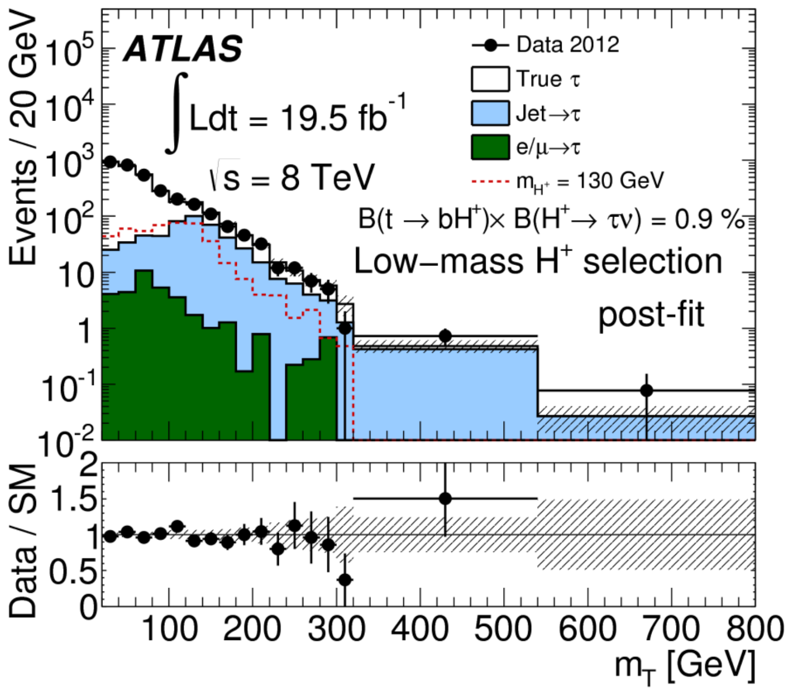
Light $H^{\pm}$: $pp \to tt \to (Wb)(H^{\pm}b) \to (q\bar{q}'b)(\tau\nu b)$

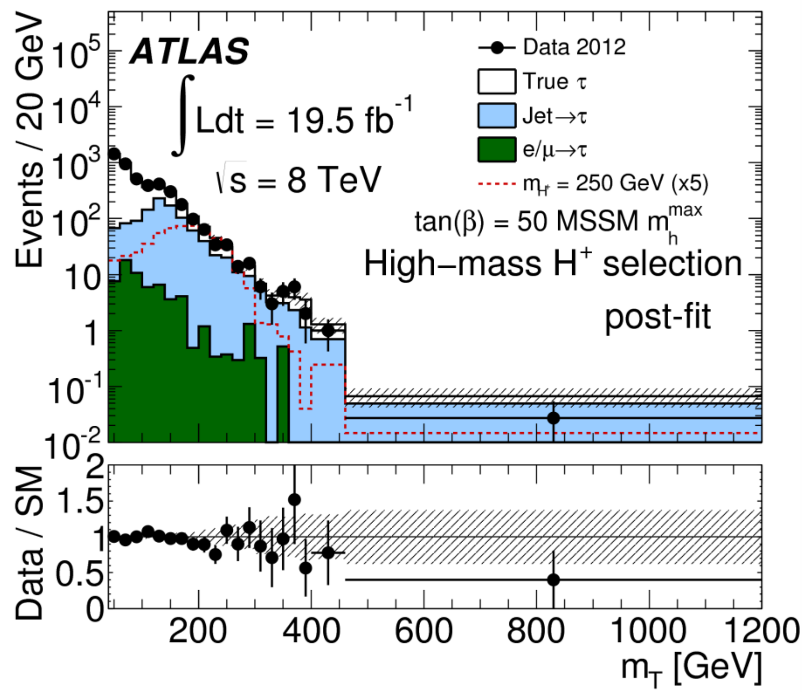
Heavy $H^{\pm}$: $pp \to tH^{\pm} \to t(\tau\nu) \to (q\bar{q}'b)(\tau\nu)$

$\Rightarrow$ similar to the SM $pp \to tt$ production

Multijet decay of the top quark(s): ≥ 3 (4) jets, ≥ 1 *b*-tagged jets;

Consider only hadronic decaying tau's; m_T as the final discriminant





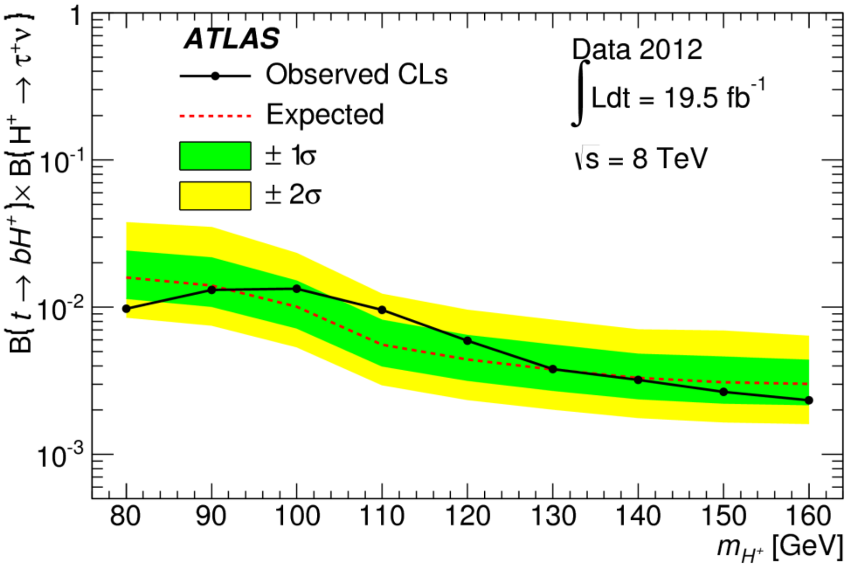
arXiv: 1412.6663

Charged Higgs Boson

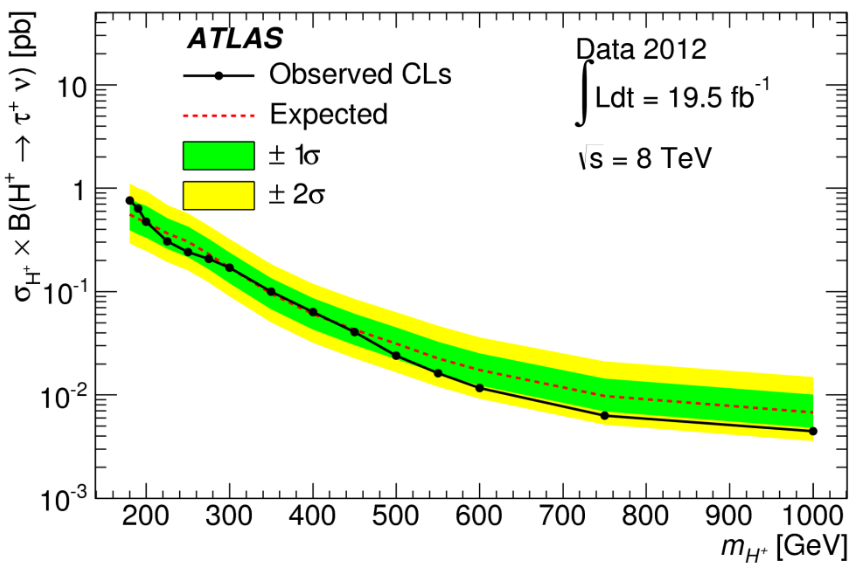
No significant excesses are observed for either analysis

Low mass: limits on $BR\left(t \to H^{+}b\right) \times BR\left(H^{+} \to \tau\nu\right)$

High mass: limits on the production rate $\sigma \times BR\left(H^{+} \to \tau\nu\right)$



Low mass: $t \to H^{+}b$



High mass: $gg \to tH^{+}b$

Note the gap in the mass coverage between 160 and 200 GeV.

Searches for $H^{\pm} \to tb$ are tough.

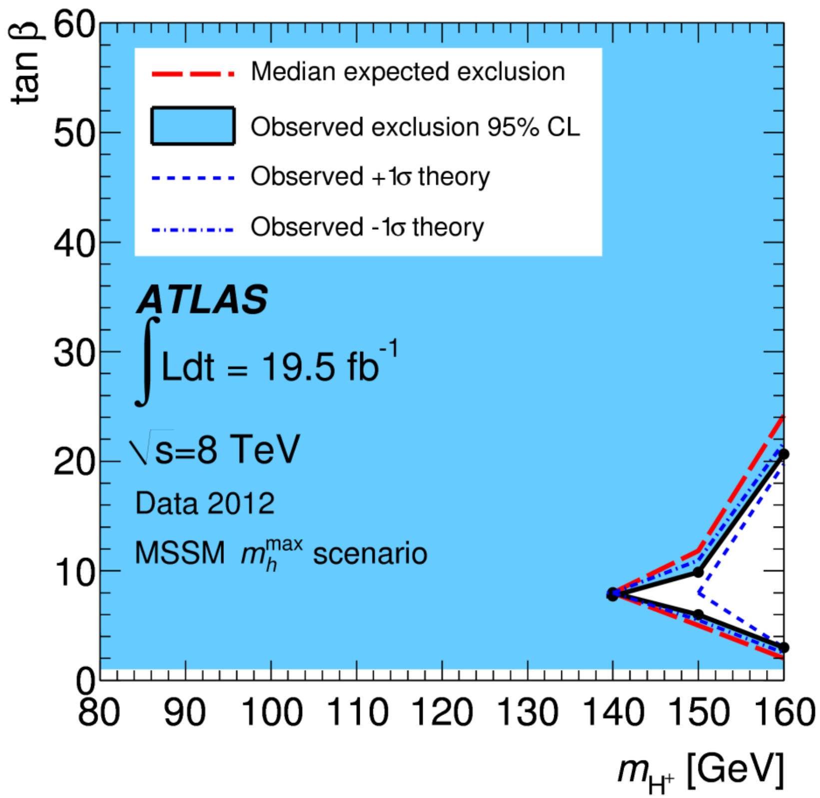
Charged Higgs Boson

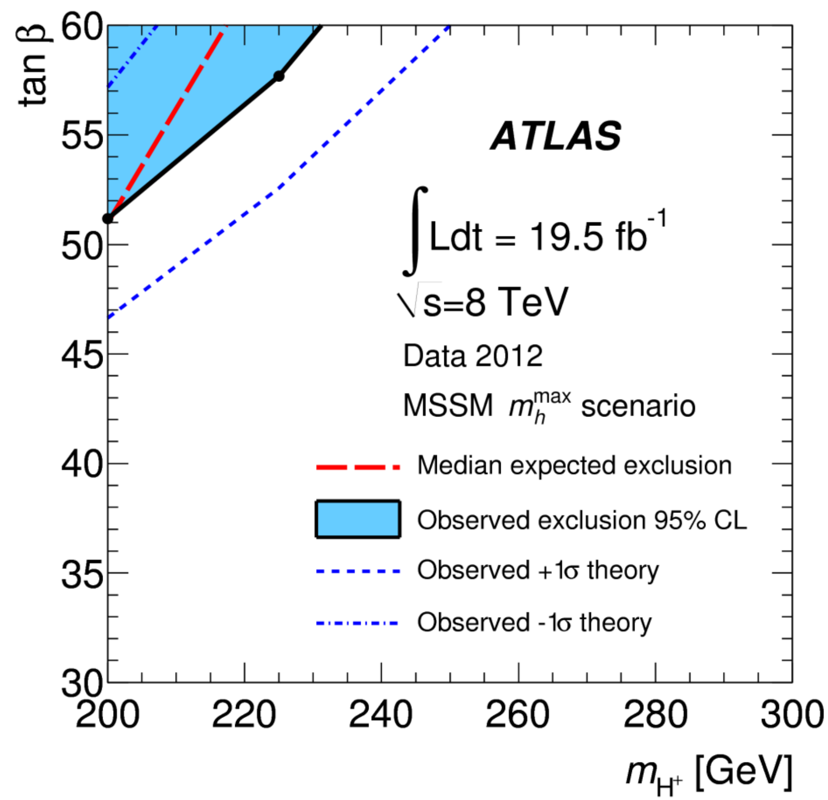
Light $H^{\pm}$:

stringent experimental constraints on most of the parameter space.

Heavy $H^{\pm}$:

only limited parameter space has been explored.

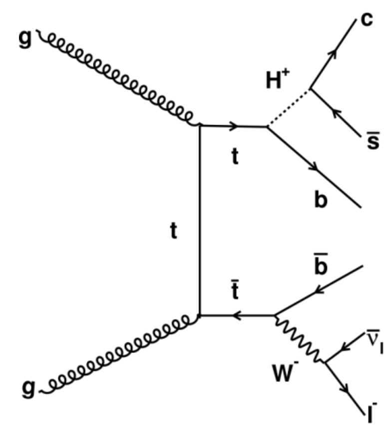




$$g_{Htb} \sim \left(m_t \cot\beta \; P_R + m_b \tan\beta \; P_L \right)$$

Charged Higgs Boson

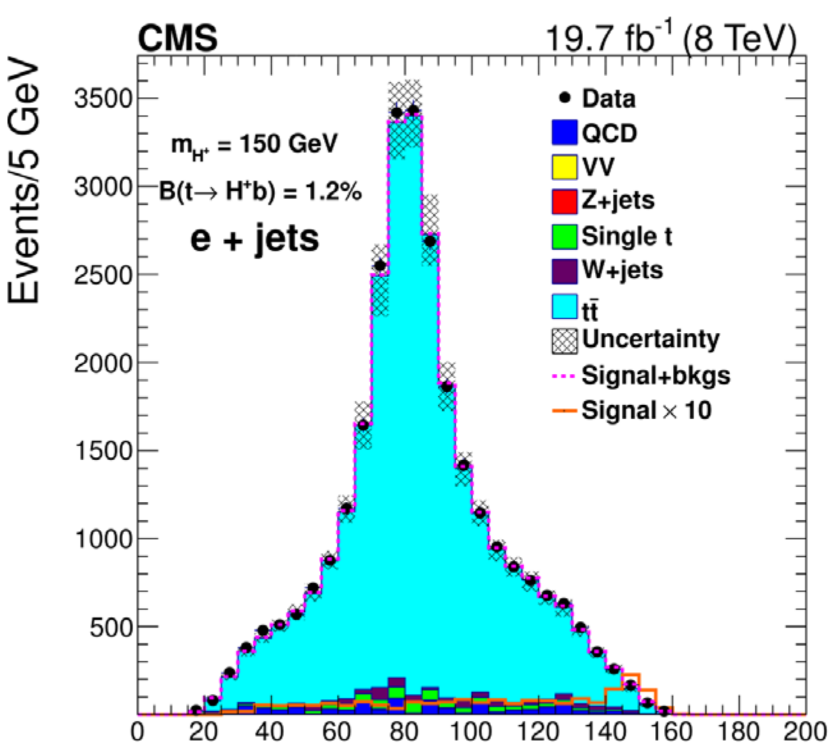
Light H$^\pm$: $pp \to tt \to (Wb)(H^\pm b) \to (\ell\nu\ b)(c\bar{s}\ b)$

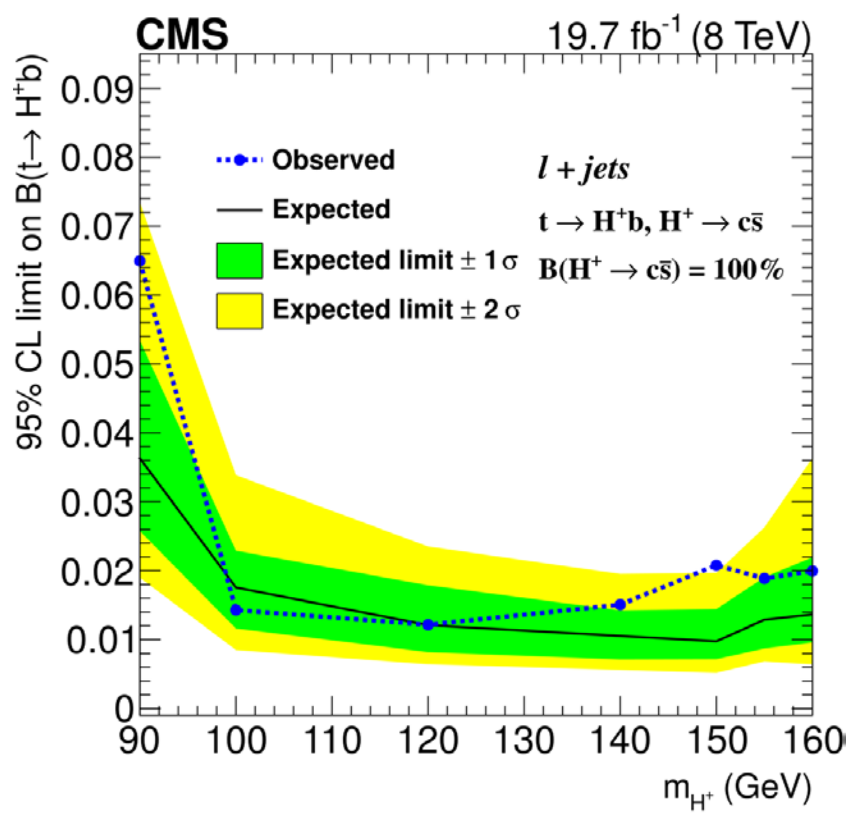


Same topology as the standard tt decay:

$tt \to (Wb)(Wb) \to (\ell\nu b)\ (qq'\ b)$

Search for additional resonance structure in dijet mass distribution



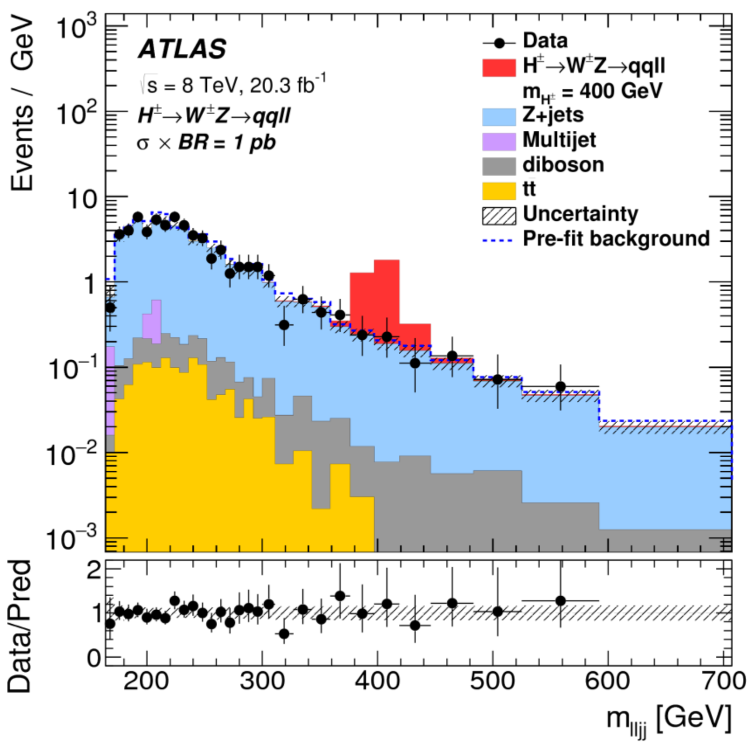


arXiv:1510.04252

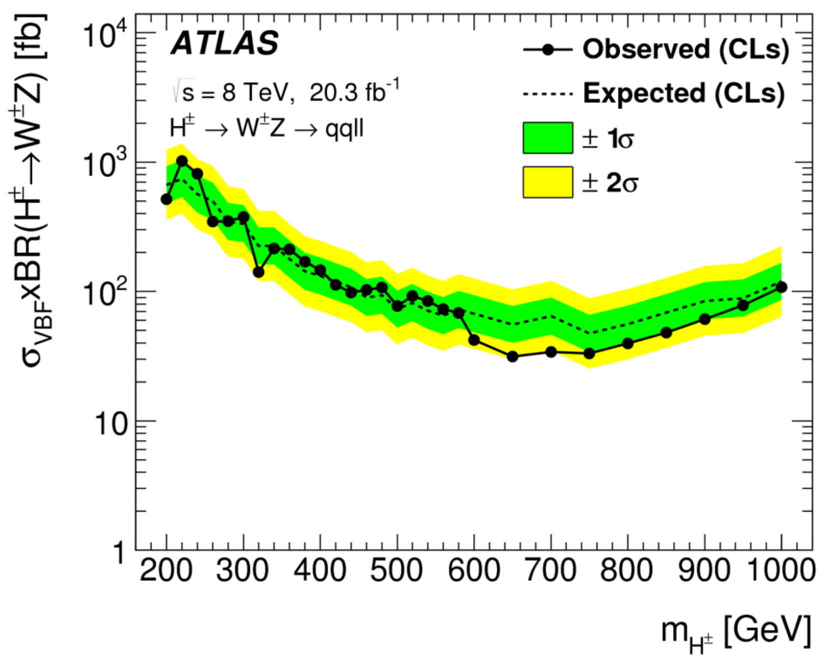
$H^{\pm} \rightarrow WZ$

$H^{\pm} \rightarrow WZ$ decay occurs at loop-level in 2HDM, but can proceed at tree-level in other models such as Higgs triplet models.

Search for the VBF production of $H^{\pm}$ with its subsequent decay of $H^{\pm} \rightarrow WZ \rightarrow qq'\ell\ell$, allowing the full reconstruction of the $H^{\pm}$ mass with a resolution of $\sim 2.5\%$.



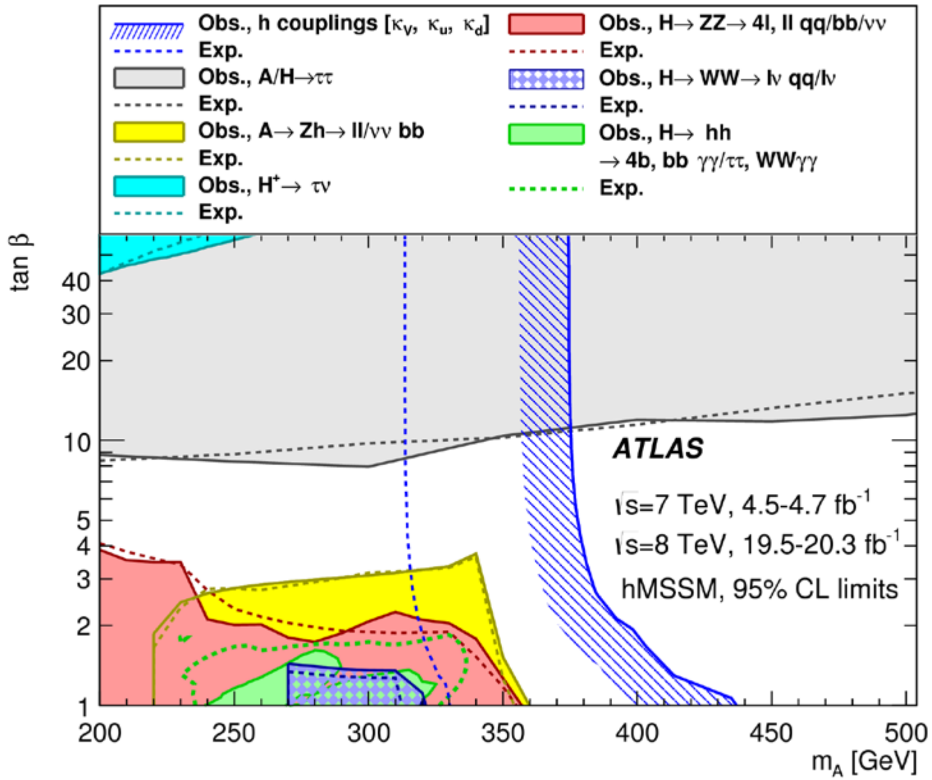
arXiv:1503.04233



Signal model: Georgi-Machacek Higgs triplet, Nucl. Phys. B262 (1985) 463.

hMSSM Scenario

Fix the mass of the light CP-even Higgs boson to 125 GeV, large supersymmetry breaking scale $M_S \gg 1$ TeV, making assumptions about mass matrix and its radiative corrections.



The coupling measurements exclude most of the region $m_A < 350$ GeV.

Summary

An extensive program in the searches of heavy Higgs bosons, Based on both theoretical motivations or experimental signatures.

Unfortunately no significant excesses have been observed. Limits are derived on the production and decays, and are interpreted in various extensions to the Standard Model.

LHC Run 2 offers significant opportunities for continuing these searches and for exploring new production and decay final states.

Backup

MSSM Tree-Level Relations

Minimal Supersymmetric Standard Model (MSSM) is a Type II 2HDM with supersymmetrized Higgs potential. At tree-level, the MSSM Higgs sector is completely determined by two parameters, often chosen to be:

- $\tan\beta$: ratio of two V.E.V
- m_A : mass of the pseudoscalar Higgs boson

With tree-level mass relations:

$$m_{H^\pm}^2 = m_A^2 + m_W^2$$

$$m_{h,H}^2 = \frac{1}{2}\left(m_Z^2 + m_A^2 \mp \sqrt{\left(m_Z^2 + m_A^2\right)^2 - 4 m_Z^2 m_A^2 \cos^2 2\beta} \right)$$

$$\cos^2(\beta - \alpha) = \frac{m_h^2\left(m_Z^2 - m_h^2\right)}{m_A^2\left(m_H^2 - m_h^2\right)} \quad \text{with} \quad \begin{cases} 0 \le \beta \le \pi/2 \\ -\pi/2 \le \alpha \le 0 \end{cases}$$

and the tree-level mass bound:

$$m_h^2 = \frac{2 m_Z^2 m_A^2 \cos^2 2\beta}{m_Z^2 + m_A^2 + \sqrt{\left(m_Z^2 + m_A^2\right)^2 - 4 m_Z^2 m_A^2 \cos^2 2\beta}} \le m_Z^2 \cos^2 2\beta$$

MSSM Scenarios

m_h^{max} the mixing parameter is chosen to maximize the mass of the light CP-even Higgs boson;

m_h^{mod} reduce amount of mixing in the top sector to be more consistent with the observed 125 GeV Higgs boson

hMSSM Fix the mass of the light CP-even Higgs boson to 125 GeV, large supersymmetry breaking scale $M_S \gg 1$ TeV, making assumptions about mass matrix and its radiative corrections.

Search for A→Zh

Combining the search in the $h \to \tau\tau$ and $h \to bb$ decay assuming SM Higgs branching ratios