Searches for BSM Higgs Bosons with ATLAS

Gabriela Navarro
Universidad Antonio Nariño
On behalf of the ATLAS Collaboration

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Outline

- BSM Higgs models.
- Search for the Neutral Higgs Boson in the MSSM.
- Search for a CP-odd Higgs Boson $A \rightarrow Zh$
- Search for Charged Higgs Bosons.
- Other BSM Higgs Bosons searches with ATLAS.
- Summary.

BSM Higgs models

Two Higgs Doublet Model (2HDM)

- Addition of a second complex Higgs doublet: ϕ_1 and ϕ_2

  If the potencial is CP conserving → 5 Higgs Bosons:
  - two CP-even scalar fields h and H
  - one pseudoscalar CP-odd field A
  - two charged fields $H^{\pm}$
- Parameters:

  m_h, m_H,m_A, $m_{H\pm}$

  α: rotation angle that diagonalizes the mass-squared matrices of the CP-even scalars.

  tan β: ratio of vacuum expectation values of the scalar fields
- Different type models:
  - Type-I: all quarks couple to ϕ_2 .
  - Type-II right-handed up quarks couple to ϕ_2 and right-handed down quarks couple to ϕ_1 .
  - Lepton specific: ϕ_1 couples to leptons and ϕ_2 to quarks.
  - Flipped: like type II but leptons couple to ϕ_2 .

MSSM

- In the MSSM model two Higgs doublets are necessary (at tree level MSSM is a type-II 2HDM).
- Beyond lowest order, benchmark scenarios are defined fixing at specific values the additional parameters.

Search for the Neutral Higgs boson of the MSSM in the ττ decay mode

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- In the MSSM, the Higgs boson couplings to τ leptons and b-quarks are strongly enhanced for a large part of the parameter space (large tan β values)
- Search in the di-τ decay mode.
- Higgs production: gluon fusion and association with b-quarks
- To reconstruct ττ system invariant mass two approaches are used:

→ MMC (Missing Mass Calculator)

→ ττ total transverse mass:

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

$$m_T = \sqrt{2 p_{T1} p_{T2}(1 - \cos(\Delta\phi)}$$

- The τ+ τ- decay channel is analyzed in these categories:

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

$\tau_{lep}\ \tau_{had}$

$\tau_{had}\ \tau_{had}$

Search for the neutral Higgs Boson in the MSSM

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τ_{lep} τ_{lep} channel
Event Selection

- Exactly 1 isolated electron and 1 isolated muon with opposite charge.
- Pt_e >15 GeV, Pt_μ > 10 GeV.
- Two categories: presence (tag) or absence (veto) of b-tagged jet

➔ Tag:

✔ exactly 1 jet satisfying b-jet id.

✔ Kinematic requirements to reduce the background from top quark decays.

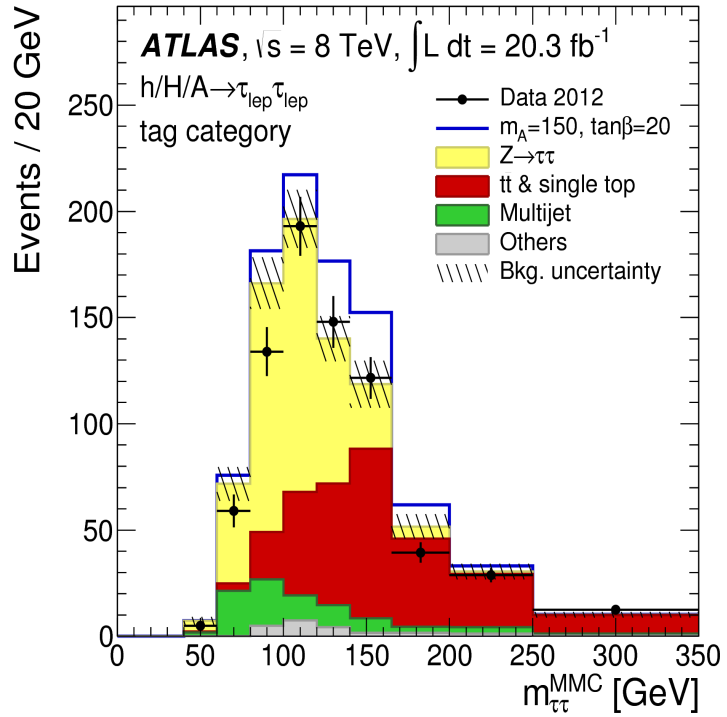
➔ Veto

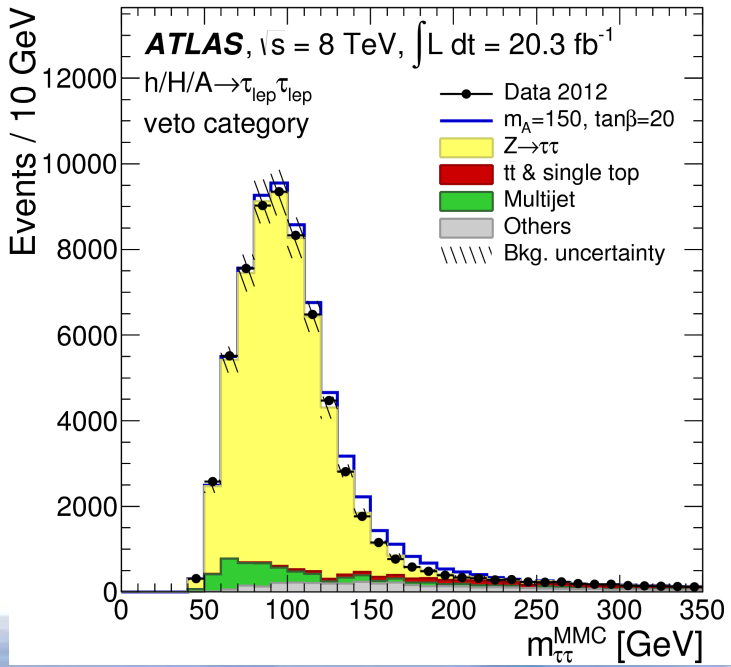
✔ No jet satifies the b-jet id criterion.

✔ Top quark background smaller → kinematic selection requirements looser.

- Main Backgrounds: Z/γ* + jets, ttbar, multijet production

- MMC mass : discriminating variable





Search for the neutral Higgs Boson in the MSSM

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$\tau_{lep}\ \tau_{had}$ channel

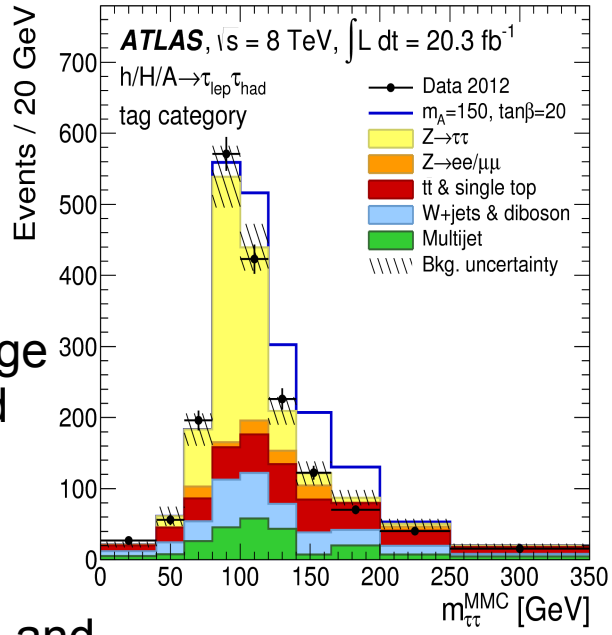
Event Selection

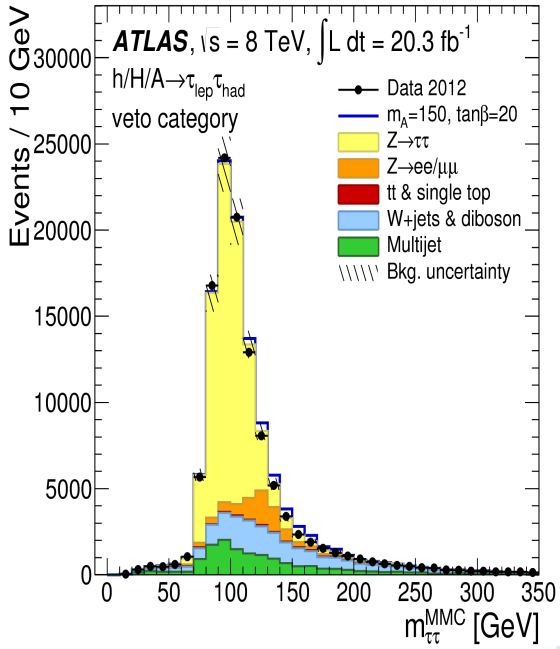
- Only 1 electron or 1 muon with pt > 26 GeV and an oppositely charge τ_{had} with pt > 20 GeV and medium id criterion.

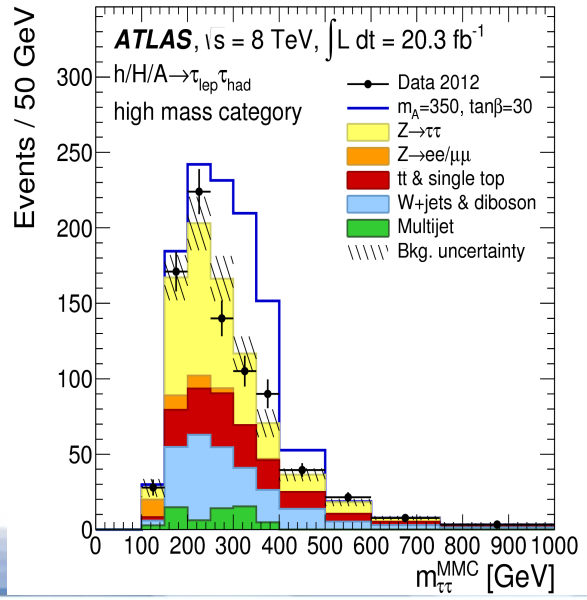
- Categories:
  - ➔ low mass region (m_A<200 GeV): tag and veto
  - ➔ high mass region ($m_A \geq 200$ GeV).

- Main Backgrounds: Z/γ* + jets, W+ jets, multijet production, top, diboson production.

- MMC mass : discriminating variable







Search for the Neutral Higgs Boson in the MSSM

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$\tau_{had}\,\tau_{had}$ channel

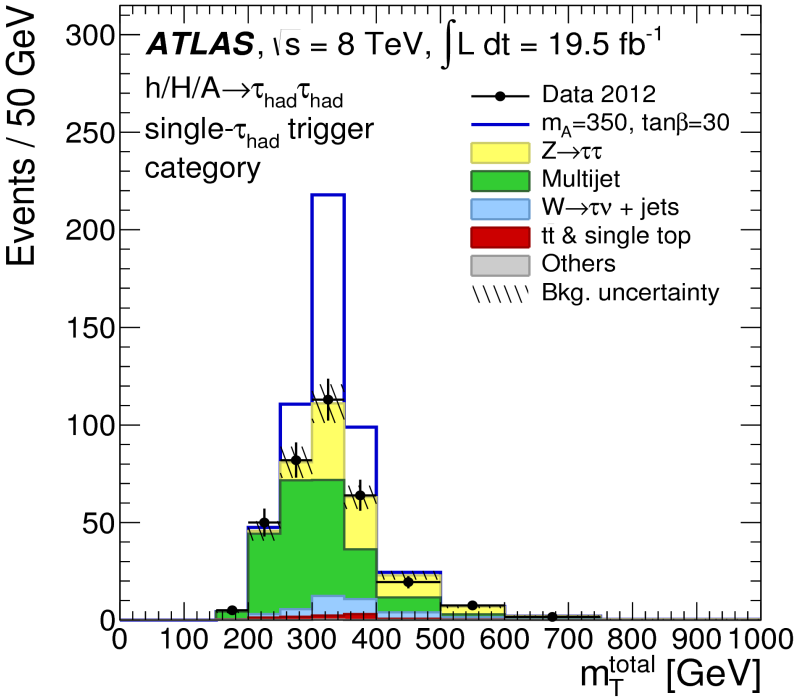
Event Selection

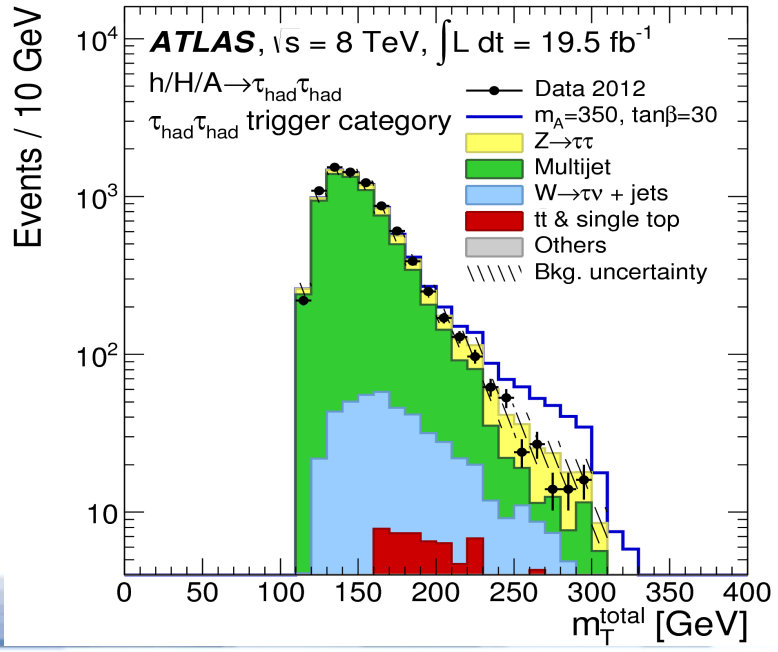
- At least, two τ_{had}. Events with e or muons rejected.
- $Pt_{\tau had}$ >50 GeV, opposite charge, $\Delta\varphi$ (τ_{had},τ_{had}) > 2.7 (back to back)

- Two categories:
  - ➔ Single τ_{had} trigger (STT)
  - ➔ $\tau_{had}\,\tau_{had}$ trigger (DTT)

- Main Background: multijet production. Less dominant: Z/γ* + jets, W+jets, ttbar, diboson production

- Discriminating variable: Total transverse mass m_T^{total}





Search for the neutral Higgs Boson in the MSSM : Results

As data is in good agreement with predicted background yields, limits are calculated.

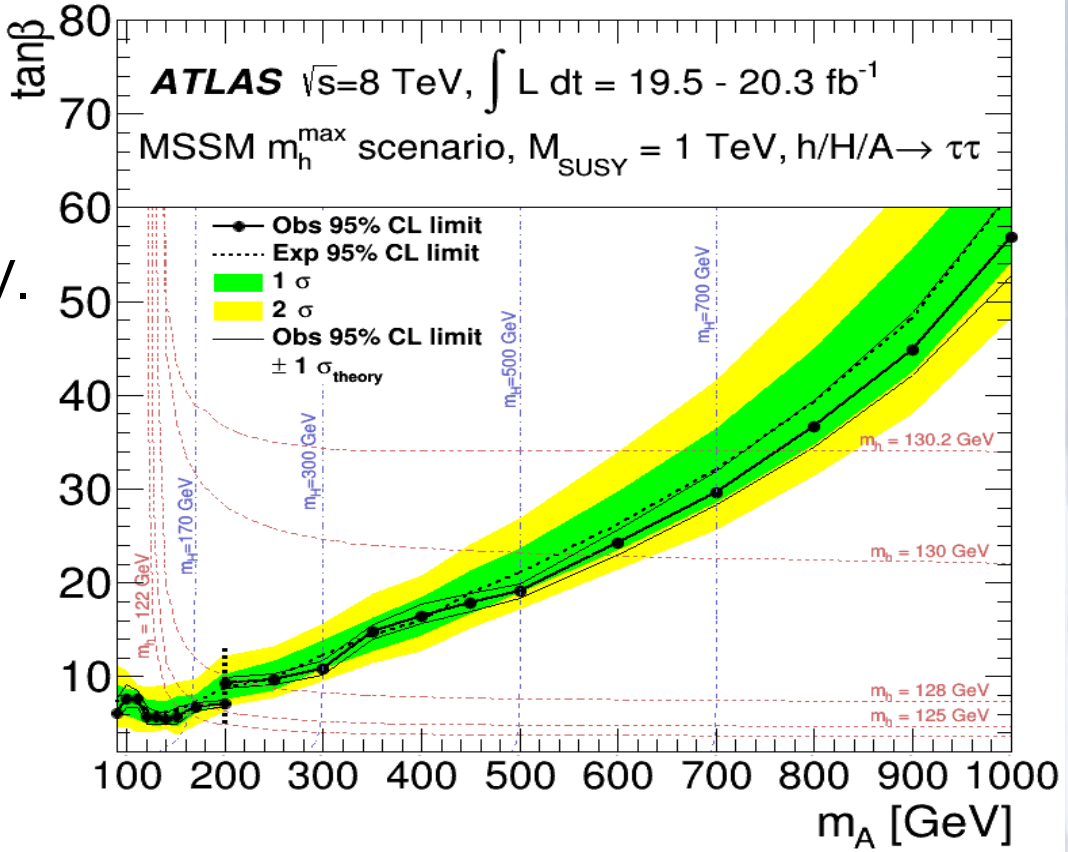
M_h^{max} scenario

Best tan β constraint:

- Excludes tanβ > 5.4 for m_A=140 GeV.
- Also, tanβ > 37 is excluded for m_A=800 GeV.

If the light CP-even Higgs of the MSSM has a mass of ~ 125 GeV then :

M_A <160 GeV is excluded for all tanβ values.
Also, tan β >10 and tan β < 4 are excluded for all m_A values.



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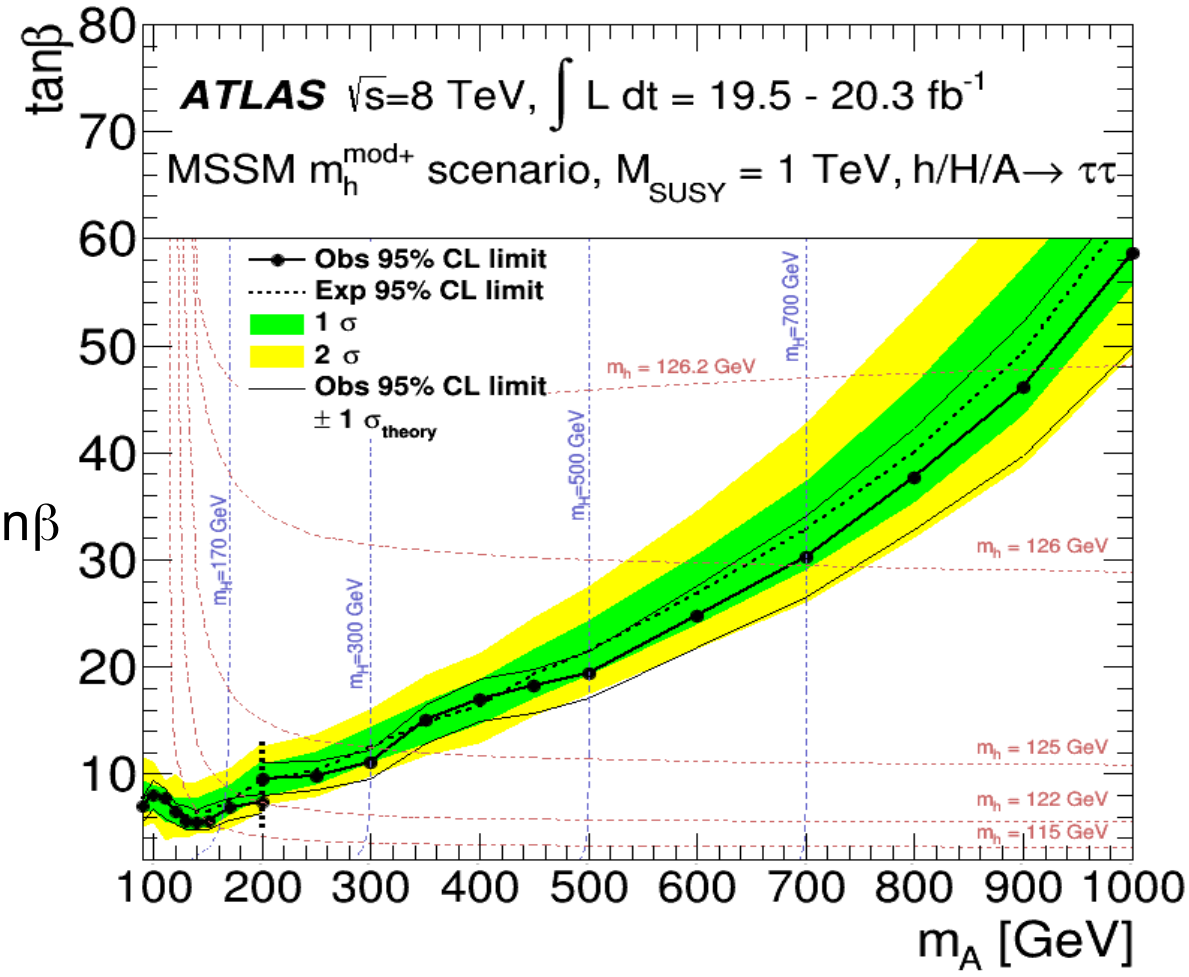
Search for Higgs Boson in the MSSM : Results

M_h^{mod} scenario

If the light CP-even Higgs of the MSSM
has a mass of ~ 125 GeV then :

M_A <200 GeV is excluded for all tanβ Values.

Also, tan β $<$ 5.5 is excluded for all m_A values.



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Search for a CP-odd Higgs Boson $A \rightarrow Zh$

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- Search for a heavy CP-odd Higgs Boson decaying into a Z boson and the h ~ 125 GeV Higgs Boson.
- $A \rightarrow Zh$ can be dominant for part of the 2HDM parameter space, especially for A mass below the ttbar threshold. In this case A is produced via gluon fusion.
- Search performed in the A mass range: 220 – 1000 GeV, reconstructing:

  $Z \rightarrow \ell\ell$ (e,μ) with $h \rightarrow bb$ or $h \rightarrow \tau\tau$

  $Z \rightarrow \nu\nu$ with $h \rightarrow bb$

- Transverse mass of Zh pair used to search for a signal
- In the search $A \rightarrow Zh \rightarrow \ell\ell\ \tau\tau$, three channels: $\ell\ell\ \tau_{had}\ \tau_{had}$, $\ell\ell\ \tau_{lep}\ \tau_{had}$, $\ell\ell\ \tau_{lep}\ \tau_{lep}$

Search for A → Zh: Z → ll, h → ττ

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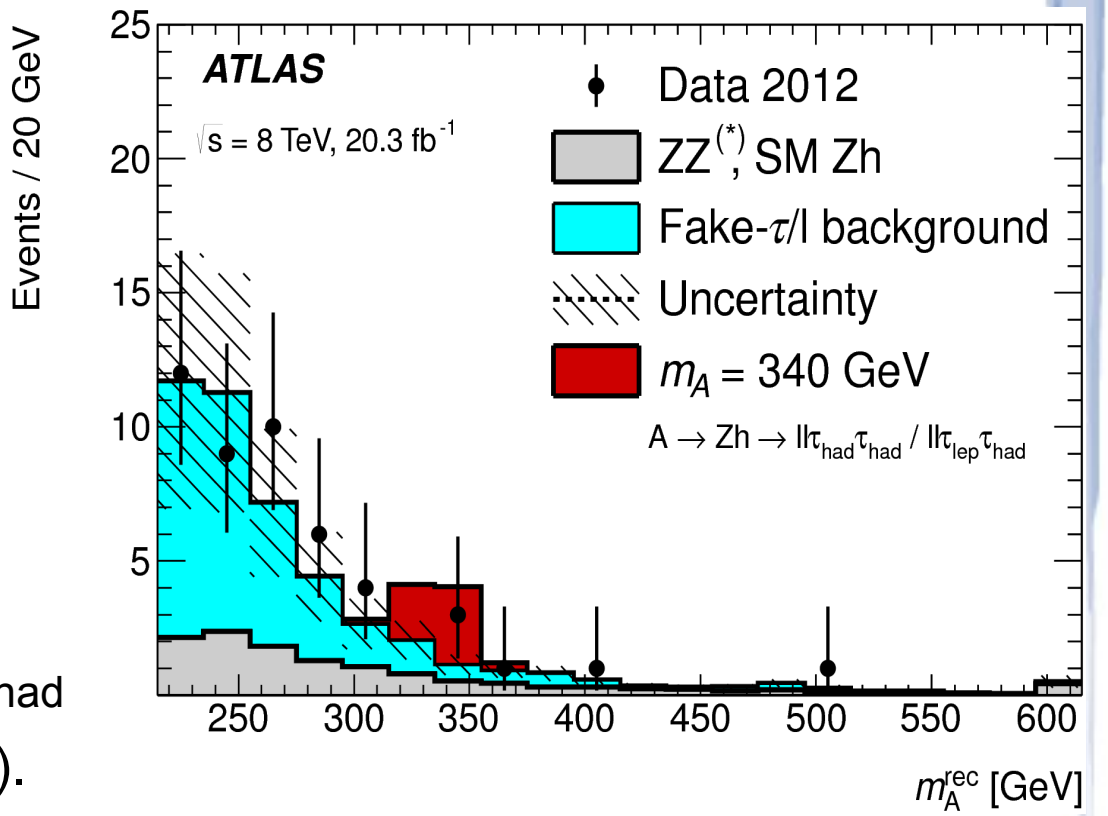
$\ell\ell + \tau_{had}\ \tau_{had}$

- Exactly 2 leptons with opposite charge and two opposite charge τ_{had}
- Loose τ_{had} identification (65% eff).
- Dominant background:" Fake τ_{had}" (Z+jets)

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

- Exactly 3 leptons and exactly one τ_{had}
- Medium τ_{had} identification (55% eff).
- Half of background: "Fake τ_{had}/ℓ" (Z+jets)
- Half of background : ZZ* production and SM Zh production (11%)



$$m_A^{rec} = m_{ll\tau\tau} - m_{ll} - m_{\tau\tau} + m_Z + m_h$$

σ x BR = 50 pb

Search for A → Zh: Z → ll, h → ττ

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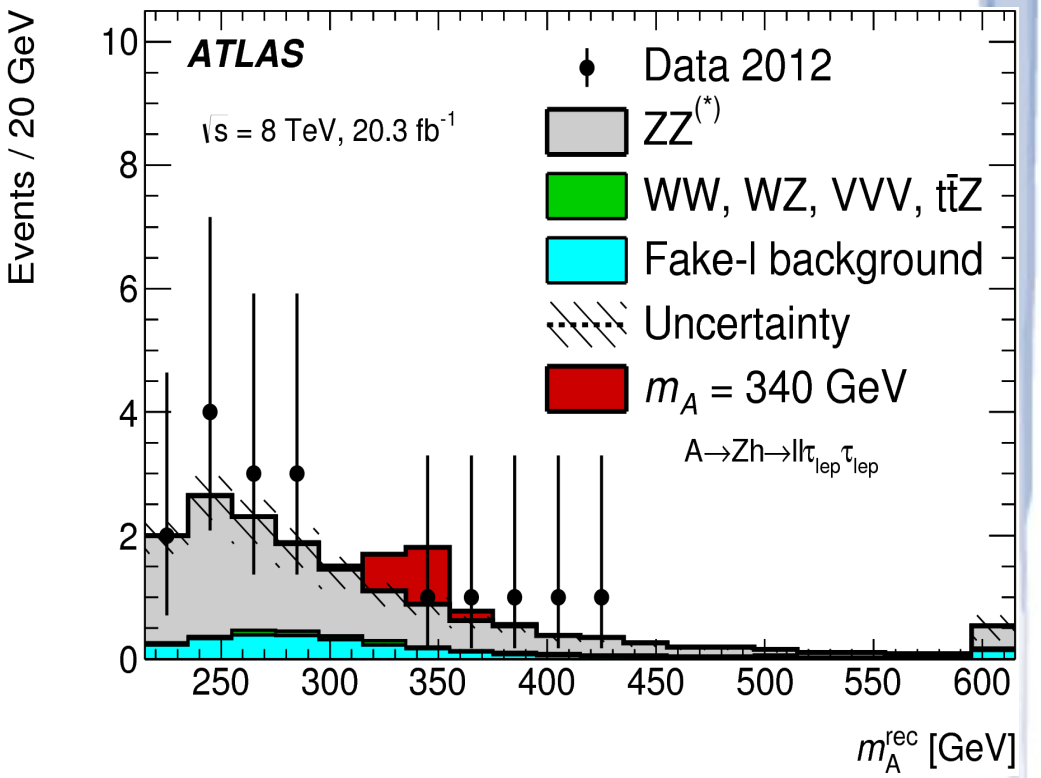
$\ell\ell + \tau_{lep}\ \tau_{lep}$

- At least 4 leptons which form:
  - ➔ one same flavour and opposite-sign pair with $80 < m_{\ell\ell} < 100$ GeV
  - ➔ same or different flavour pair with $90 < m_{\tau\tau} < 190$ GeV
- Two categories according to the lepton flavour in the h decay:
  ee, μμ SF
  eμ DF
- Main Backgrounds
  SF: ZZ* production with Z → ee, μμ
  DF: ZZ* production with Z → $\tau_{lep}\ \tau_{lep}$



σ x BR = 50 pb

$$m_A^{rec} = m_{ll\tau\tau} - m_{ll} - m_{\tau\tau} + m_Z + m_h$$

Search for A → Zh: Z → ℓℓ / νν, h → bb

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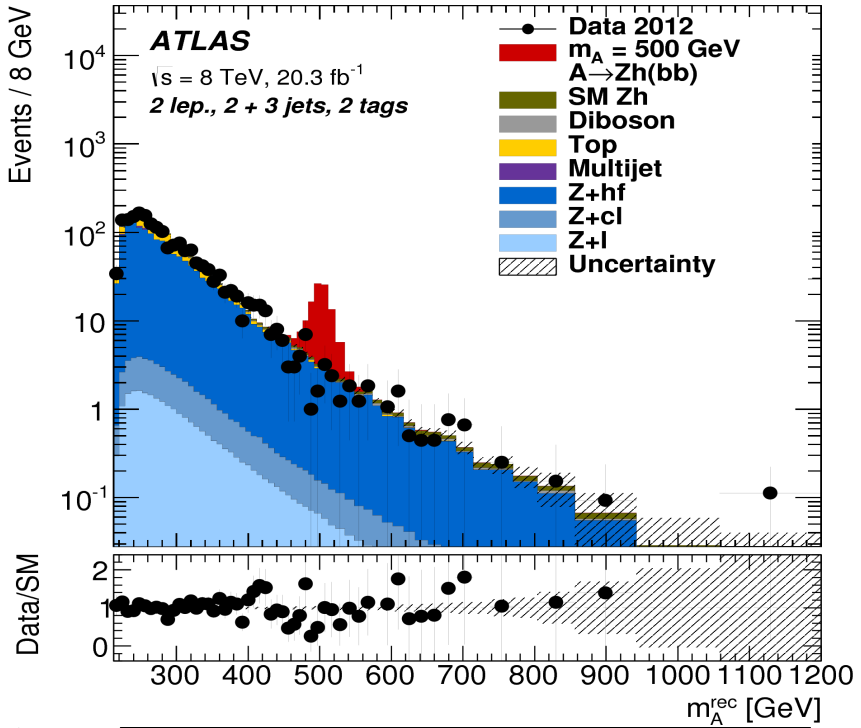
ℓℓ + bb

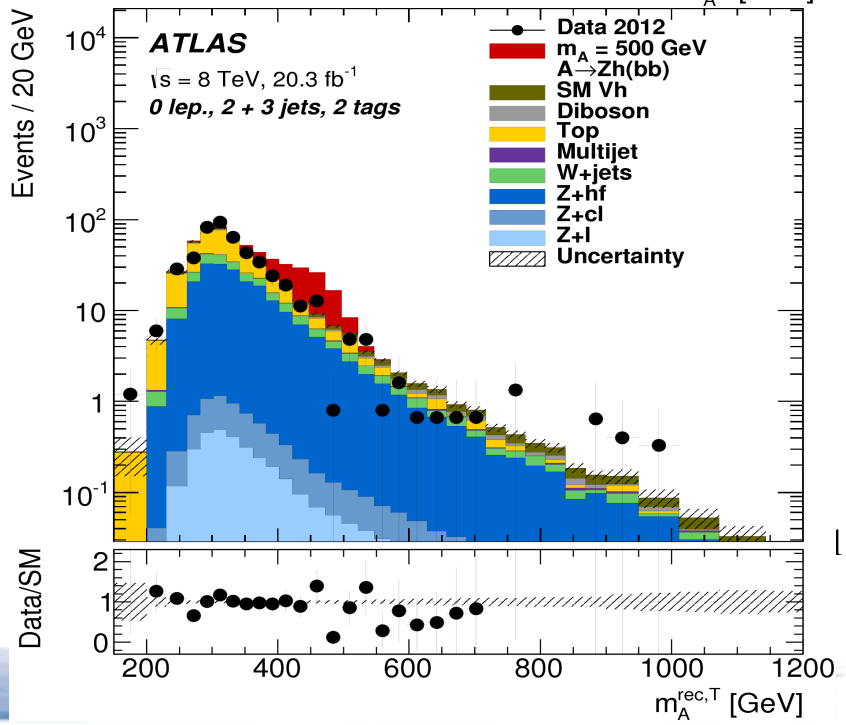
- Two electrons or 2 muons with pT > 7 GeV.
- $83 < m_{\ell\ell} < 99$ GeV
- Two b-tagged jets with pT> 45 (20) GeV
- h → bb decay selected requiring $105 < m_{bb} < 145$ GeV.
- Backgrounds: Z+jets, top-quark

νν + bb

- $E_T^{MISS} > 120$ GeV, $p_T^{MISS} > 30$ GeV.
- No electrons and muons with pT > 7 GeV.
- Same jet selection as ℓℓbb + veto of additional jets.
- h → bb decay selected requiring $105 < m_{bb} < 145$ GeV.
- Requirements on angular quantities.
- Backgrounds: Z+jets, W+jets, top-quark, multijets

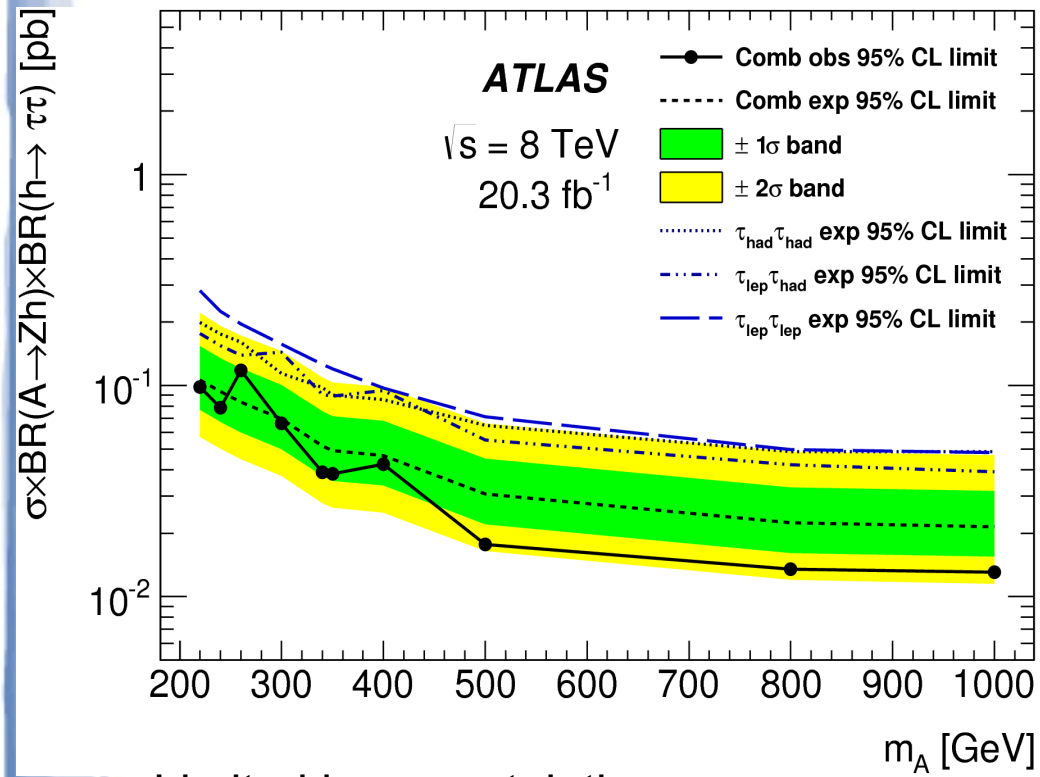
$$m_A^{rec} = \sqrt{(E_T^{bb} + E_T^{miss})^2 - (\vec{p}_T^{bb} + \vec{E}_T^{miss})^2}$$





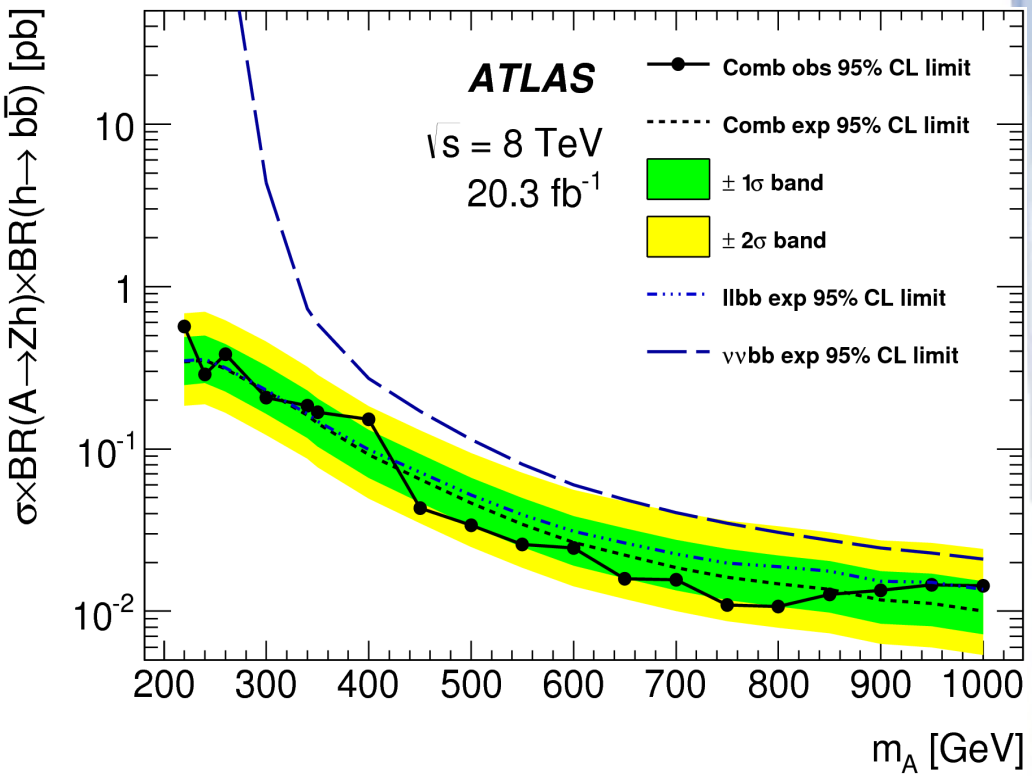
Search for A → Zh : Results

Exclusion limits at the 95% CL are set on the
$\sigma(gg \rightarrow A) \times BR(A \rightarrow Zh) \times BR(h \rightarrow bb/\tau\tau)$



Limited by uncertainties on:

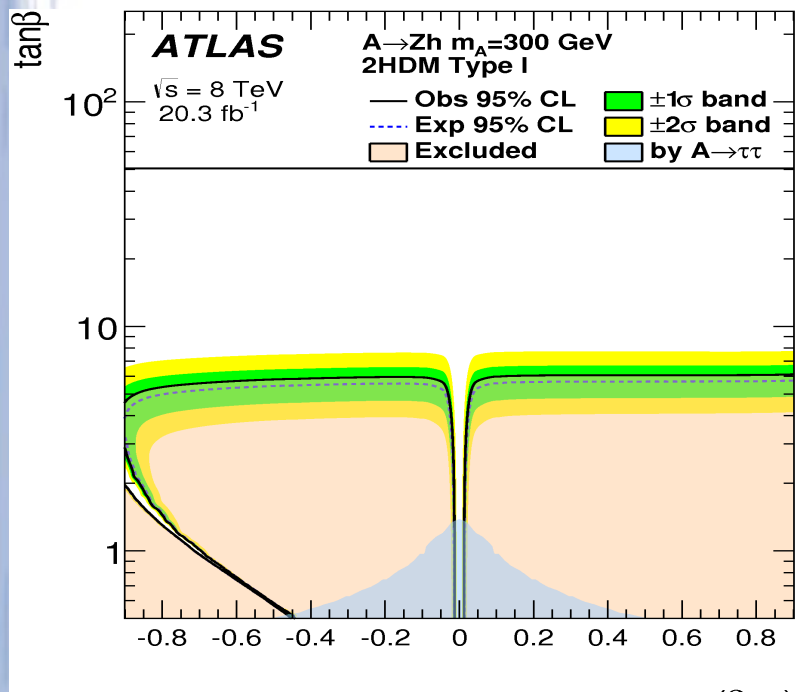
- Background theoretical cross section
- τ_{had} identification and energy scale
- Fake $\tau_{had/\ell}$

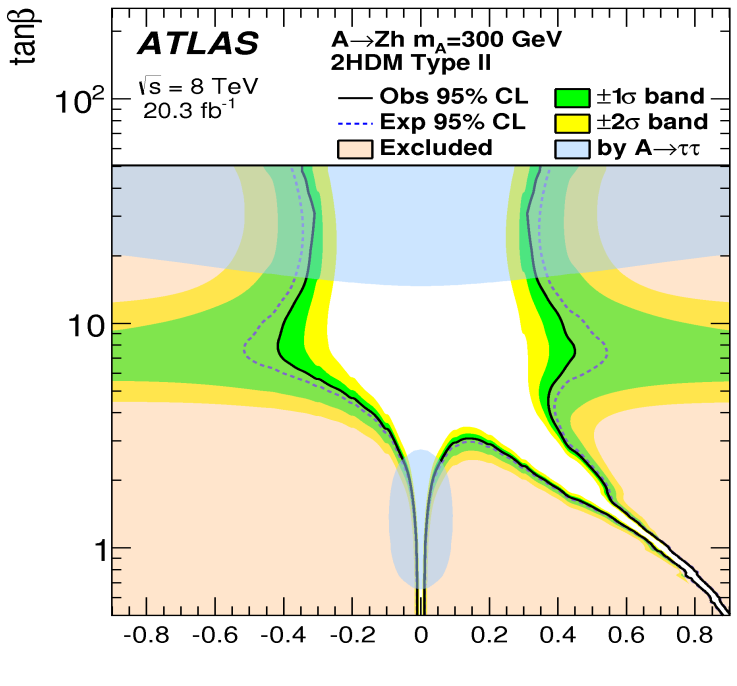


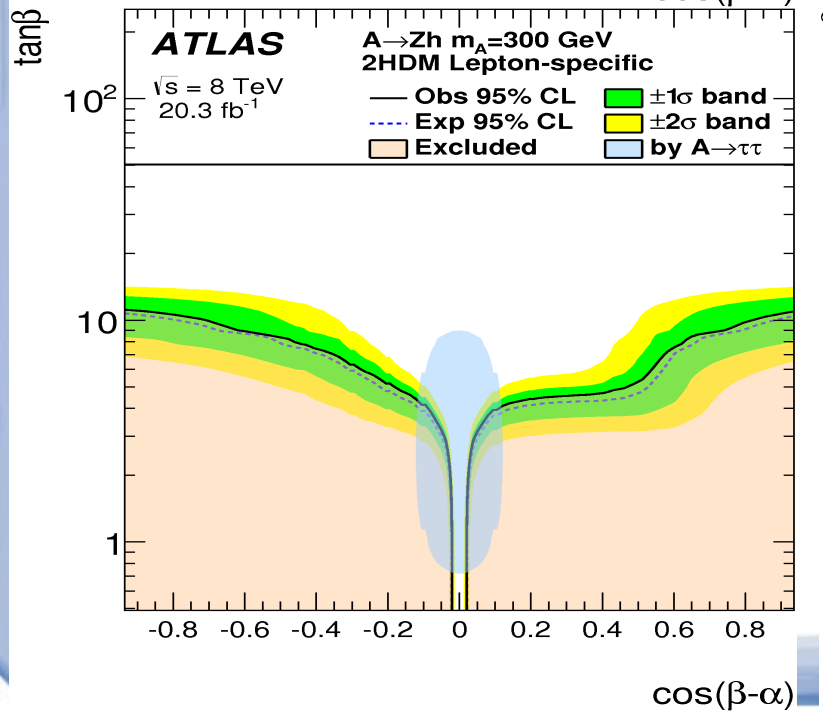
Limited by uncertainties on:

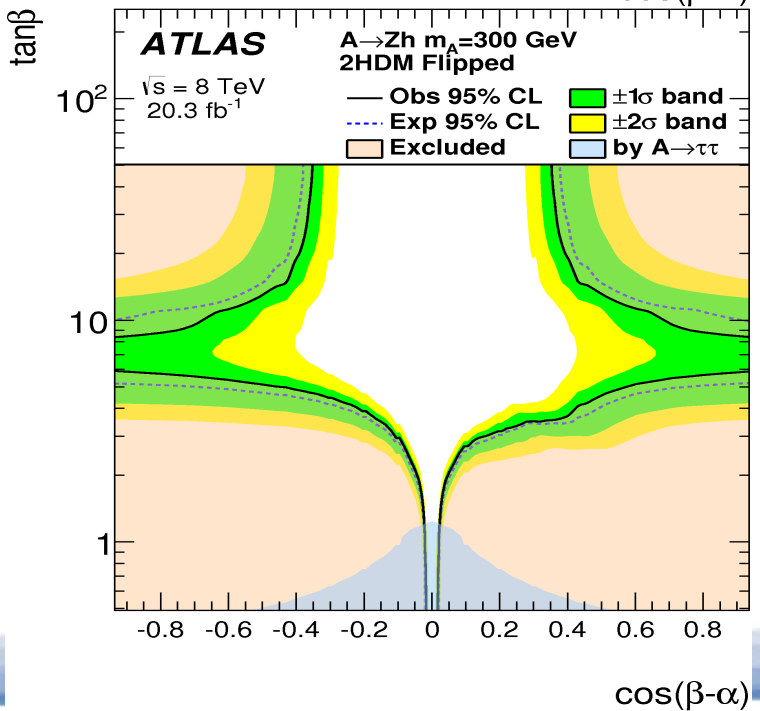
- Jet energy scale
- B-tagging efficiency

Search for A → Zh : 2HDM interpretations









Assumptions:

$$m_A = m_H = m_{H^\pm}$$
$$m_h = 125\,GeV$$
$$m_{12}^2 = \frac{m_A^2 \tan\beta}{(1+\tan^2\beta)}$$
$$m_A = 300\,GeV$$

Blue shaded area denotes previous A → ττ searches excluded regions.

Search for Charged Higgs $H^{\pm} \rightarrow \tau\nu$

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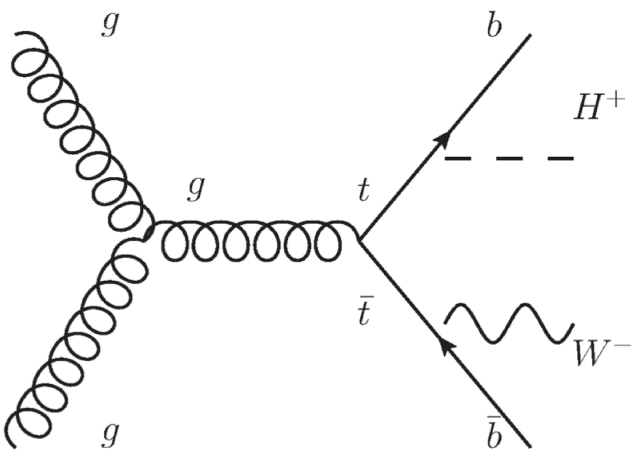
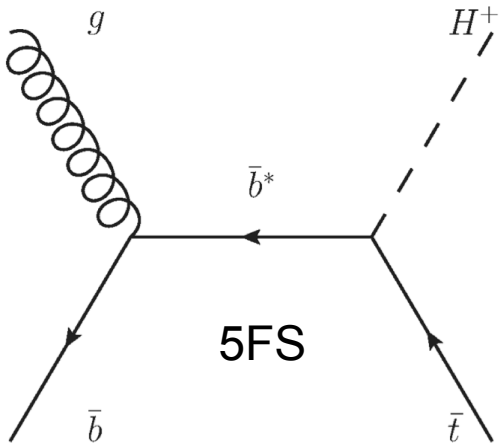
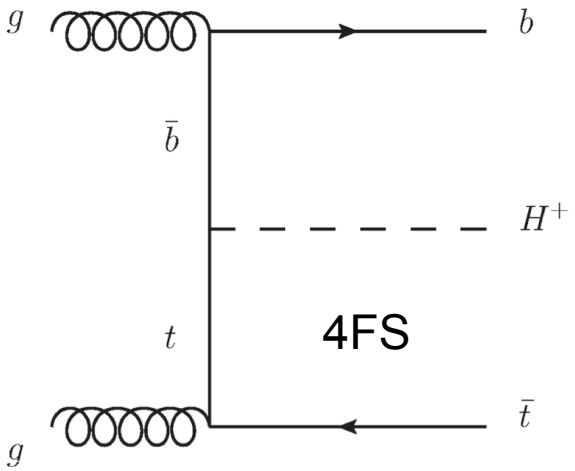
- Charged Higgs Bosons are predicted by several BSM models, such as 2HDM or models with Higgs triplets.

Light charged Higgs
$m_H < m_{top}$
Production $t \rightarrow H^{\pm} b$



Heavy charged Higgs
$m_H > m_{top}$
Production via top quark association





Decay mode: $H^{\pm} \rightarrow \tau^{\pm} \nu$
Charged Higgs mass ranges: 80 - 160 GeV, 180 – 1000 GeV.
Final state:

- Presence of τ_{had} , E_t^{miss}, b-quark jets, hadronically decaying W.
- Absence of any isolated e or μ with high pT.

Search for Charged Higgs $H^{\pm} \rightarrow \tau^{\pm} \nu$

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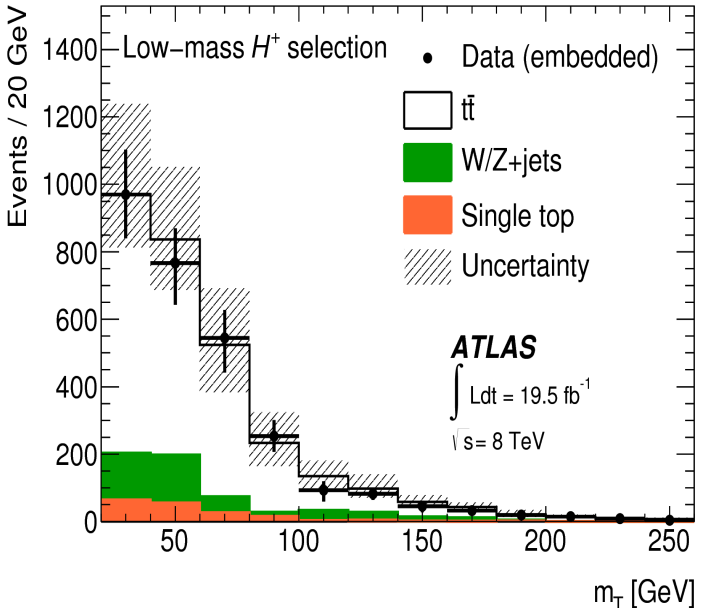
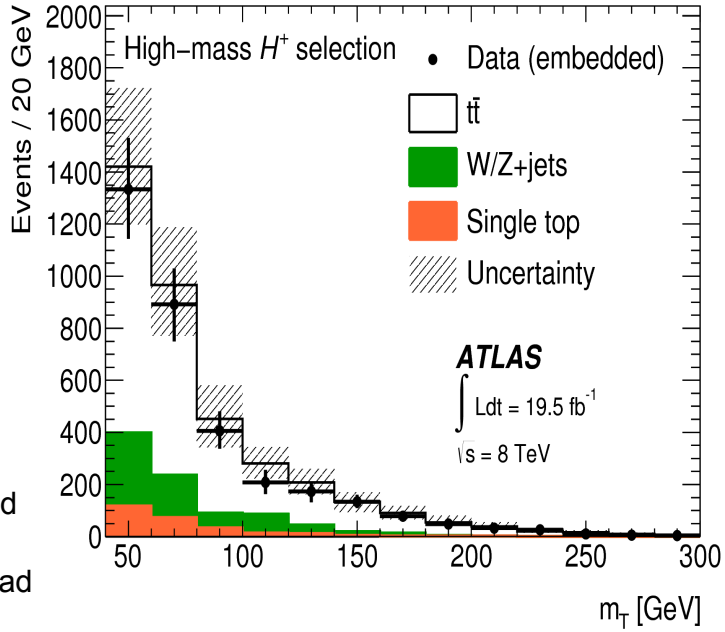
Event selection

- Trigger: τ_{had} + E_T^{miss} trigger.
- At least 4 (3) selected jets for low-mass (high).
- At least one of these jets being b-tagged.
- Exactly one τ_{had} with pT > 40 GeV.
- No e or μ in the event.
- E_t^{miss} > 65 (80) GeV.
- Discriminating variable: transverse mass

$$m_T = \sqrt{2 p_T^{\tau} E_T^{miss} (1 - \cos \Delta\phi_{\tau,miss})}$$





Backgrounds

- Data-driven estimation for backgrounds that contain a real τ_{had} from a vector boson decay and backgrounds with a jet misidentified as τ_{had}
- Small contribution from e/μ misidentified as τ_{had} is estimated from simulations.

Search for Charged Higgs $H^{\pm} \rightarrow \tau^{\pm} \nu$: Results

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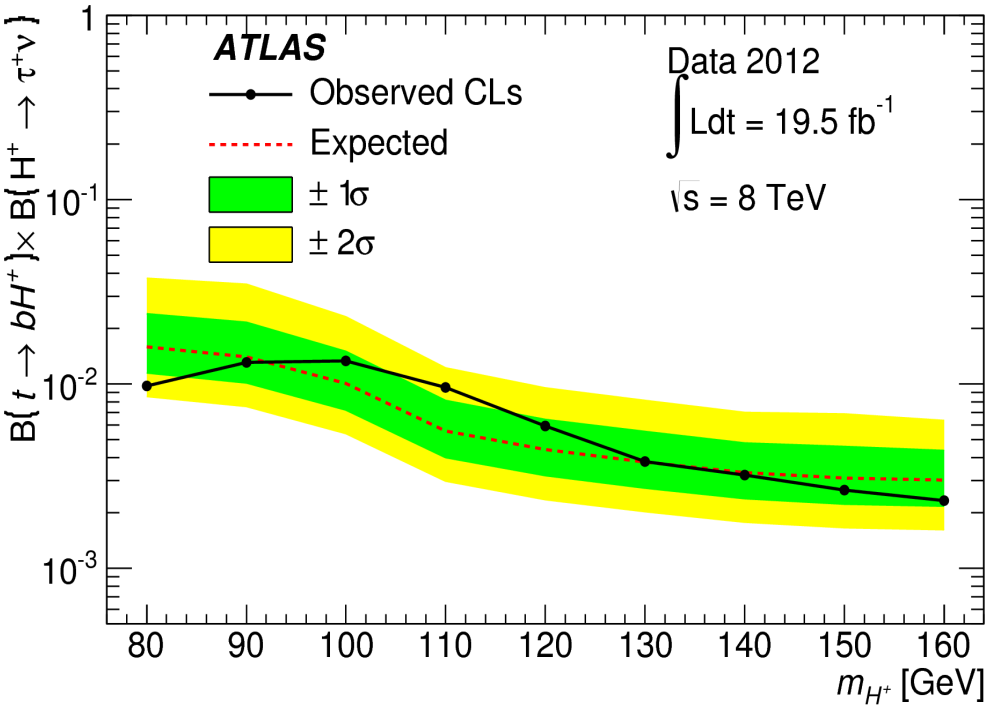
Low-mass

Exclusion limits at 95% CL on:

$BR(t \rightarrow bH^{\pm}) \times BR(H^{\pm} \rightarrow \tau^{\pm} \nu)$

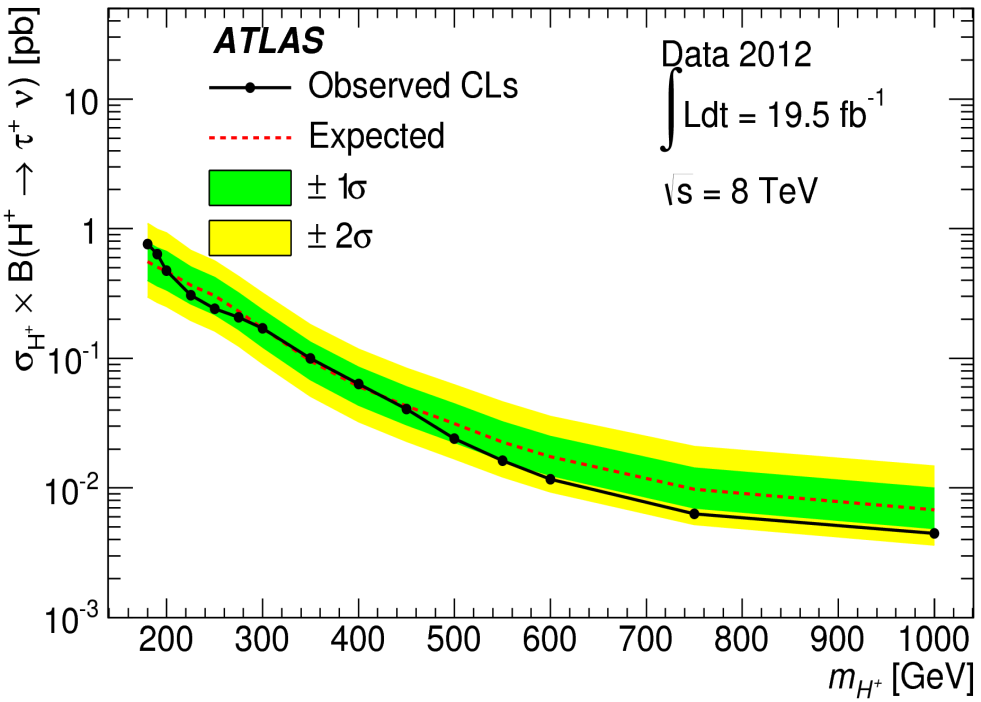


BR < 0.23 – 1.3 %

High-mass

Exclusion limits at 95% CL on:

$\sigma(pp \rightarrow tH^{\pm} + X) \times BR(t \rightarrow bH^{\pm}) \times BR(H^{\pm} \rightarrow \tau^{\pm} \nu)$



σ x BR < 0.79 pb – 4.5 fb

Main systematic uncertainties:

- Measurement of the trigger efficiency
- Simulation of the detector response to τ_{had}

Main systematic uncertainties

- Multi-jet background
- True τ_{had} background

Search for Charged Higgs $H^{\pm} \rightarrow \tau^{\pm} \nu$: MSSM

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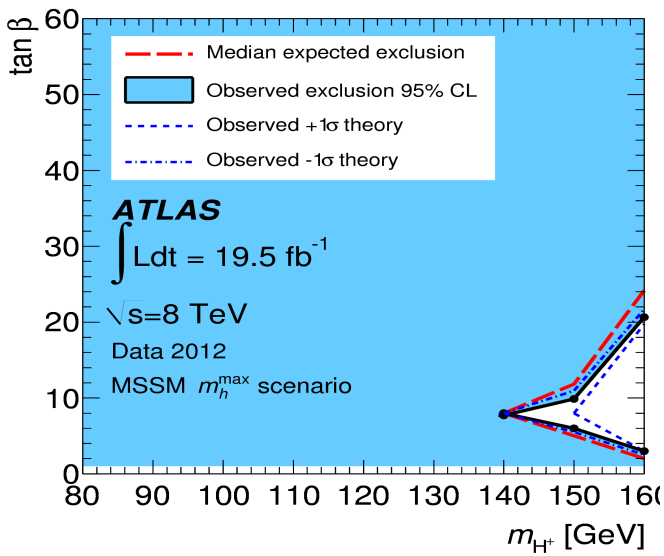
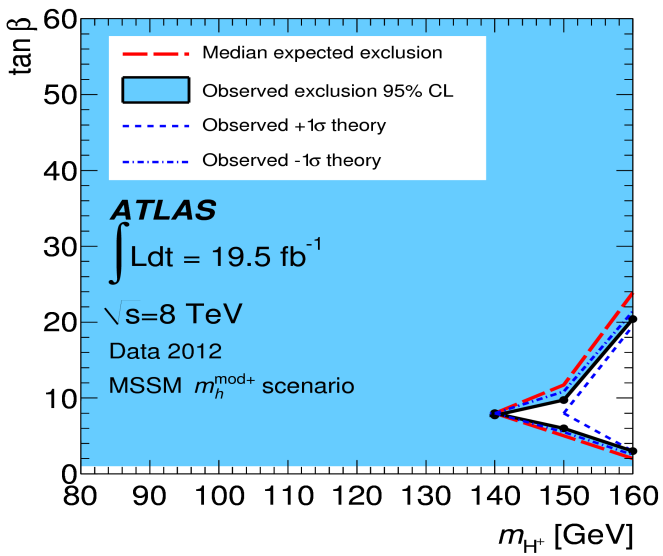
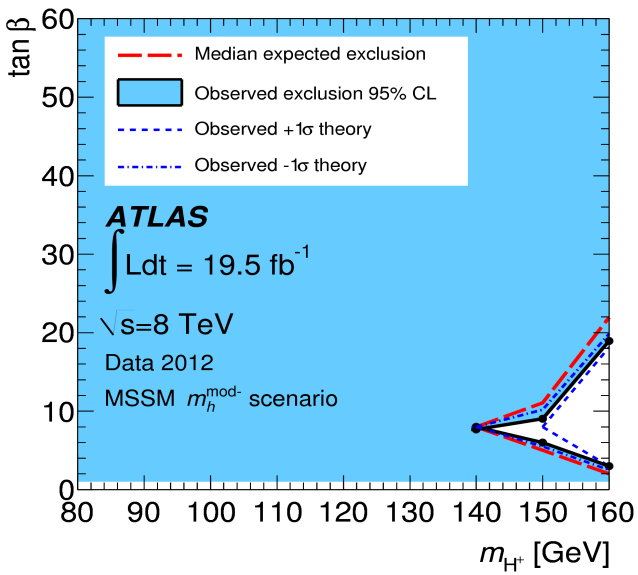
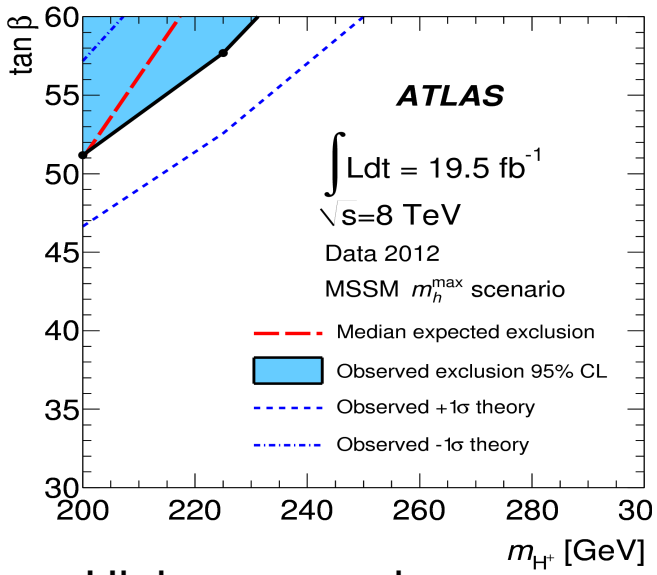
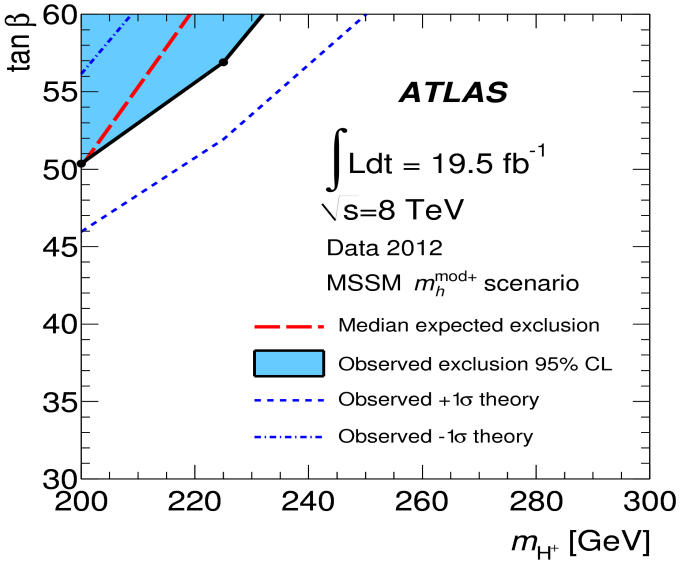
Low mass region:
Almost all values for tan β > 1 are excluded in the different scenarios

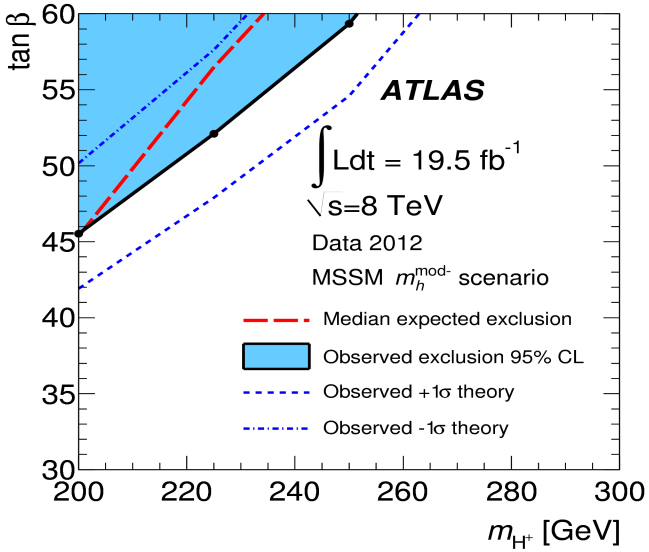












High mass region:
Values of tan β > 45 – 50 are excluded in a mass range 200 GeV < $m_{H^{\pm}}$ < 250 GeV

Other ATLAS BSM Higgs Bosons searches

- Search for Higgs Boson in the NMSSM [arXiv:1505.01609, submitted to PRD].
- Higgs to invisible : search for SM Higgs boson decaying to DM.
  - In association with hadronically decaying vector Boson [arXiv:1504.04324, accepted EPJC].
  - VBF production [ATLAS-CONF-2015-004]
- Higgs triplet models: $H^{\pm} \rightarrow W^{\pm} Z$ [Phys. Rev. Lett. 114, 231801 (2015)]
- $H \rightarrow ZZ_d \rightarrow 4\ell$, $H \rightarrow Z_d Z_d \rightarrow 4\ell$ [arXiv:1505.07645, submitted to PRD].
- Search for additional heavy Higgs boson in the $H \rightarrow ZZ$ decay [arxiv:1507.05930, submitted to EPJC]
- Search for Higgs Boson Pair Production in the $\gamma\gamma$ bb final State: $H \rightarrow hh \rightarrow bb\ \gamma\gamma$ [Phys. Rev. Lett. 114, 081802 (2015)]
- Search for Higgs boson pair production in the b bbar b bbar final state: $H \rightarrow hh \rightarrow$ bb bb [arXiv:1506.00285, submitted to EPJC].

Summary

- Three recent ATLAS searches for BSM Higgs Boson have been presented:
- Search for neutral Higgs Bosons of MSSM
  - $h/H/A \rightarrow \tau\tau$
  - Results interpreted in the MSSM parameter space for m_h^{max}, m_h^{mod+} and m_h^{mod-} benchmark scenarios.
- Search for CP-odd Higgs Boson decaying to Zh ($A \rightarrow Zh$)
  - Considering $\ell\ell\ \tau_{had}\ \tau_{had}$, $\ell\ell\ \tau_{lep}\ \tau_{had}$, $\ell\ell\ \tau_{lep}\ \tau_{lep}$, $\ell\ell bb$, $\nu\nu bb$ final states.
  - Results interpreted in 2HDM

Summary

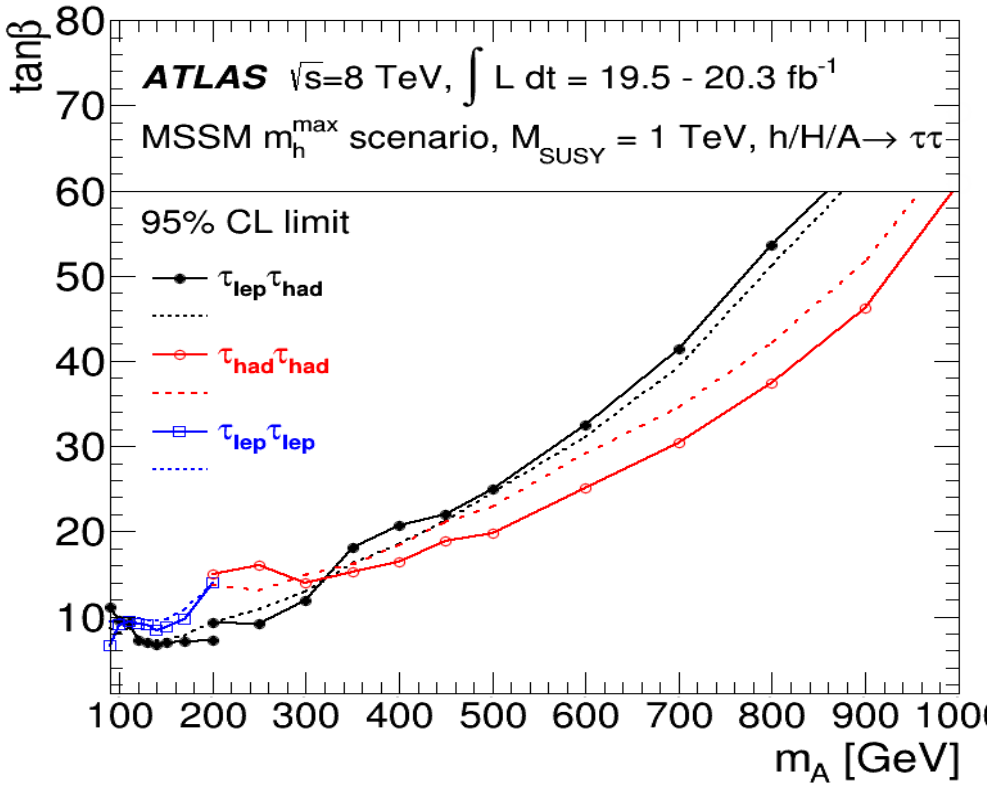
- Search for charged Higgs decaying to $\tau\nu$ ($H^{\pm} \rightarrow \tau^{\pm}\ \nu$)
  - ➔ Low-mass and high-mass regions
  - ➔ Results interpreted in the MSSM parameter space for m_h^{max}, m_h^{mod+} and m_h^{mod-} benchmark scenarios.

- More analyses are coming in Run 2

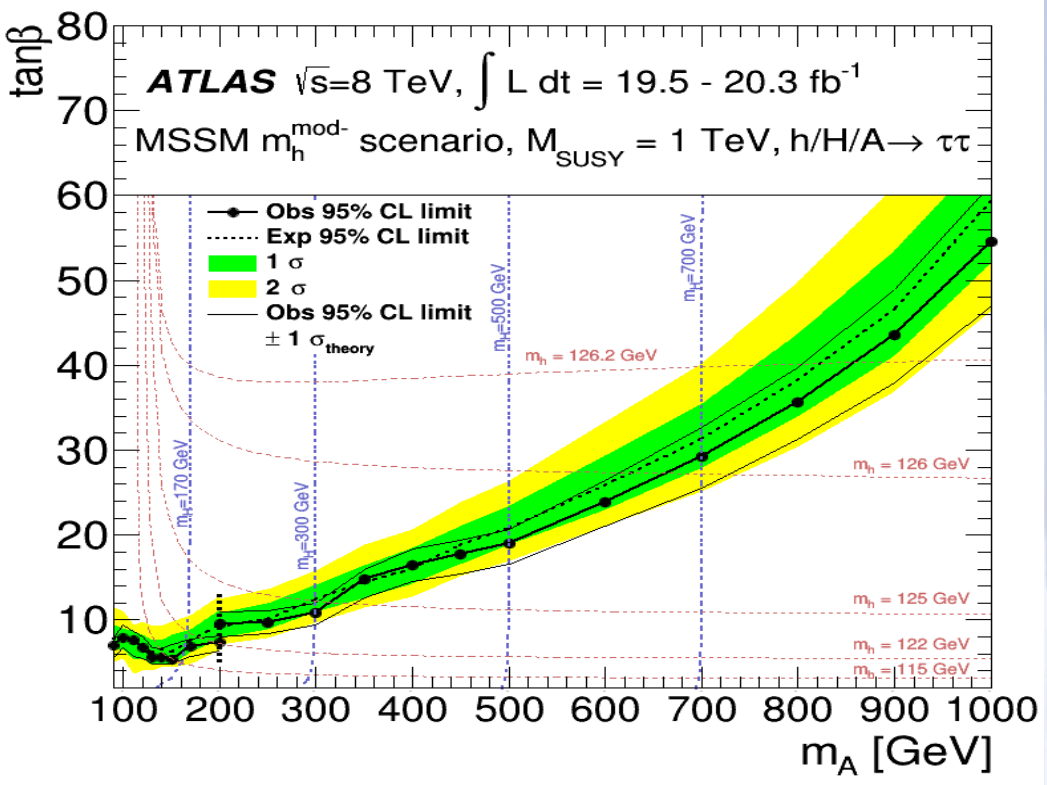
  Exciting time for searches! Stay tuned!

Back

Search for the Neutral Higgs boson of the MSSM



Limits for MSSM m_h^{max} per channel



Limits for MSSM m_h^{mod-}

Search for the Neutral Higgs Boson in the MSSM

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	$\tau_e\tau_\mu$		$\tau_{\text{lep}}\tau_{\text{had}}$		$\tau_{\text{had}}\tau_{\text{had}}$	
	Signal [%]	Background [%]	Signal [%]	Background [%]	Signal [%]	Background [%]
Data-driven methods	-	$^{+3}_{-4}/2$	-	14/4	-	7/0
Cross-section	$^{+14}_{-18}/^{+14}_{-17}$	4/5	$^{+14}_{-19}/^{+14}_{-17}$	3/4	$^{+14}_{-19}/^{+14}_{-17}$	2/2
Acceptance modelling	$20/^{+4}_{-2}$	4/5	$^{+14}_{-20}/^{+1}_{-3}$	6/9	$^{+14}_{-17}/^{+2}_{-1}$	$^{+9}_{-6}/5$
e/μ selection	3/3	4/4	2/2	1/2	-	-
τ selection	-	-	4/4	3/5	11/11	4/5
b-tagging	5/0	2/0	$^{+4}_{-8}/1$	$^{+7}_{-6}/0$	6/0	0/0
Energy scale	$^{+4}_{-7}/1$	$^{+4}_{-6}/1$	$^{+5}_{-13}/7$	$^{+8}_{-10}/11$	$^{+37}_{-30}/^{+21}_{-16}$	$^{+12}_{-9}/6$
Luminosity	4/4	3/4	4/4	3/3	4/4	1/1
Total	$^{+25}_{-29}/^{+15}_{-18}$	$^{+9}_{-10}/9$	$^{+22}_{-32}/^{+17}_{-19}$	$^{+18}_{-20}/16$	$^{+44}_{-41}/^{+28}_{-26}$	$^{+17}_{-13}/9$

Summary of systematic uncertainties on the estimated signal and background event yields in the ττ decay channels. All numbers are in per cent.

The signal uncertainties are for the parameter choice m_A=150GeV and tanβ=20.

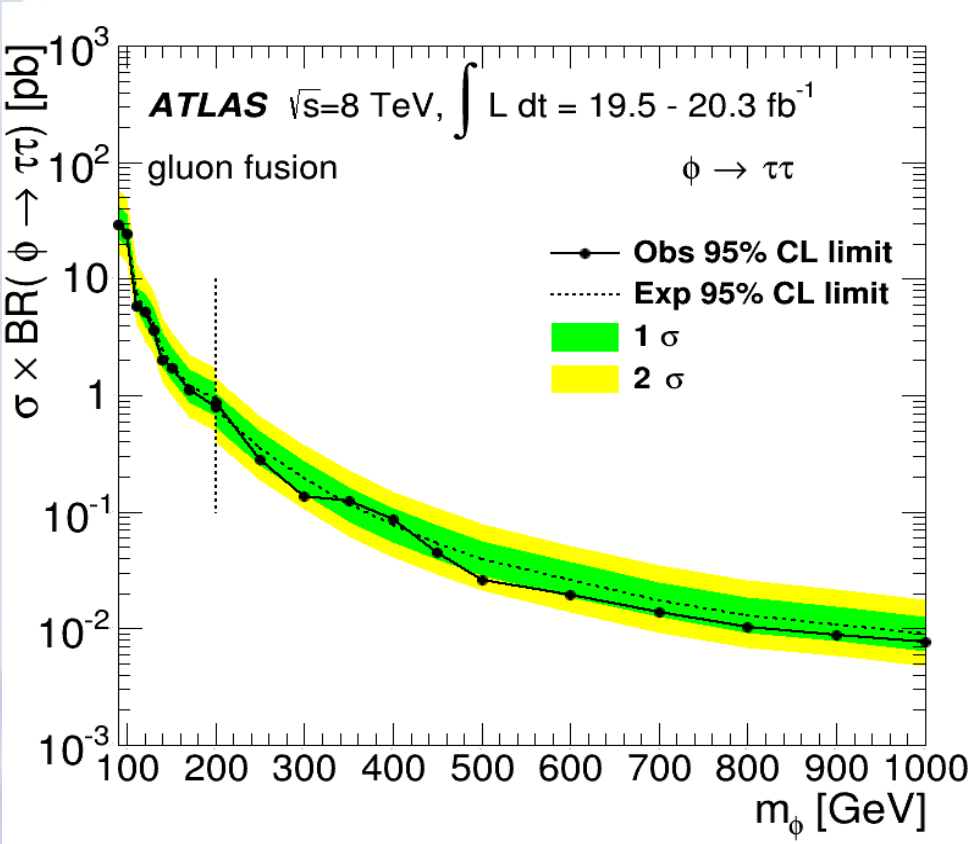
The first number in each entry refers to the b-tagged sample and the second to the b-vetoed sample.

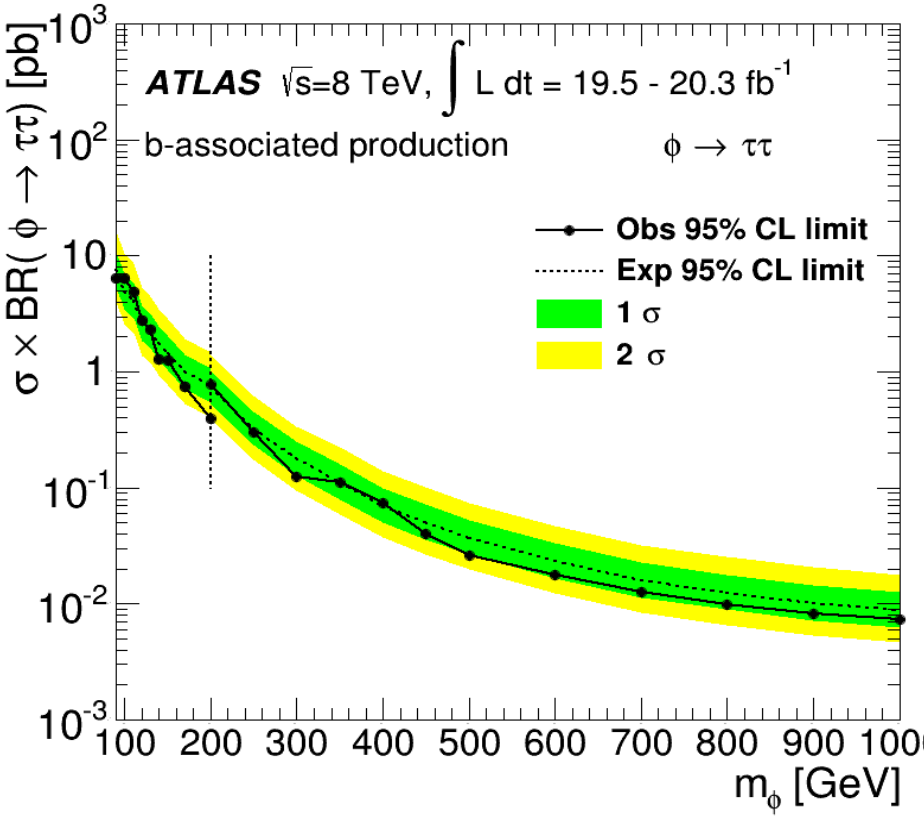
Search for Neutral Higgs boson of the MSSM

Single scalar boson ϕ, with narrow width relative to experimental mass resolution

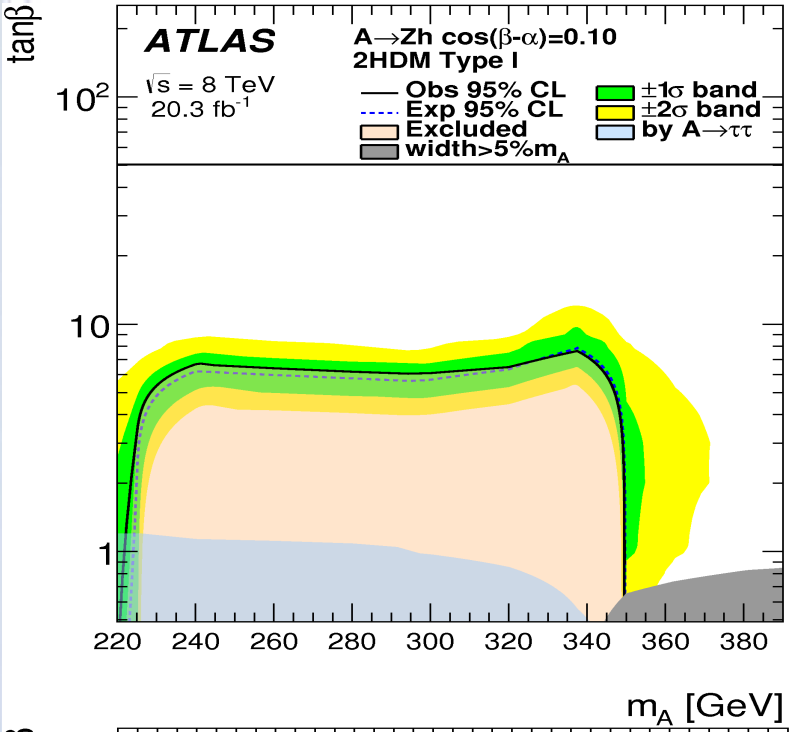
Exclusion region:
σ x BR > 29 pb for $m\phi$ = 90 GeV to
σ x BR > 7.4 fb for $m\phi$ = 1000 GeV

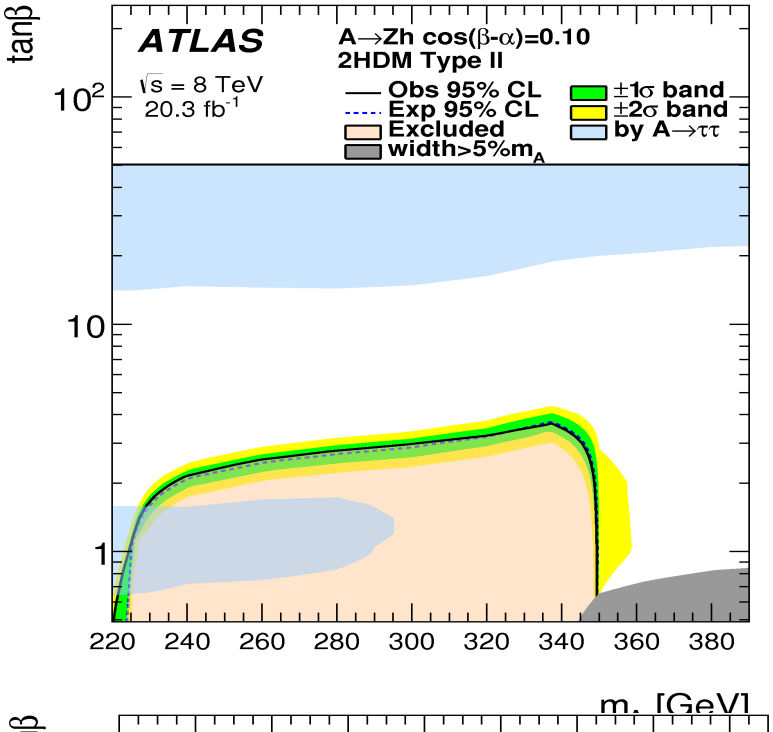
Exclusion region:
σ x BR > 6.4 pb for $m\phi$ = 90 GeV to
σ x BR > 7.2 fb for $m\phi$ = 1000 GeV

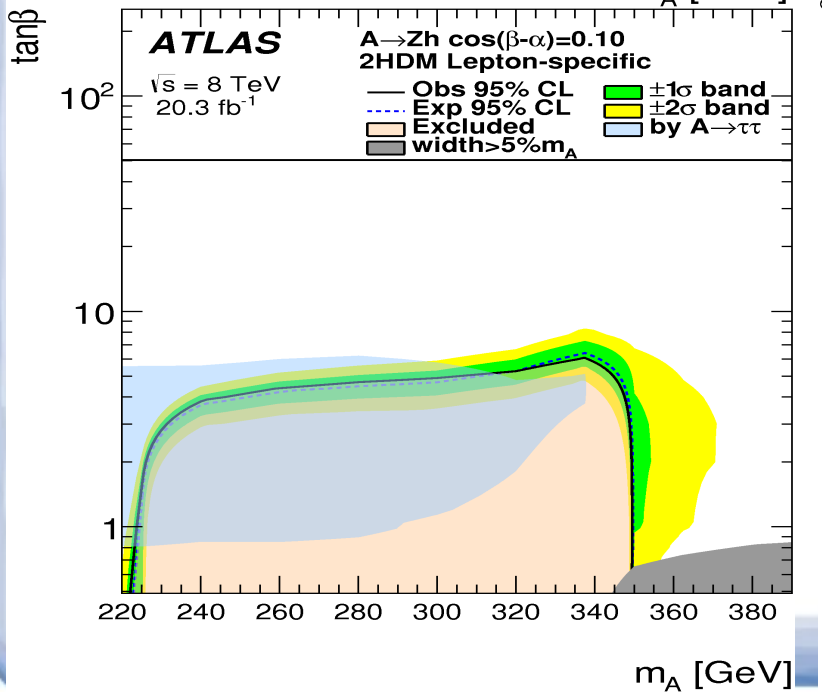


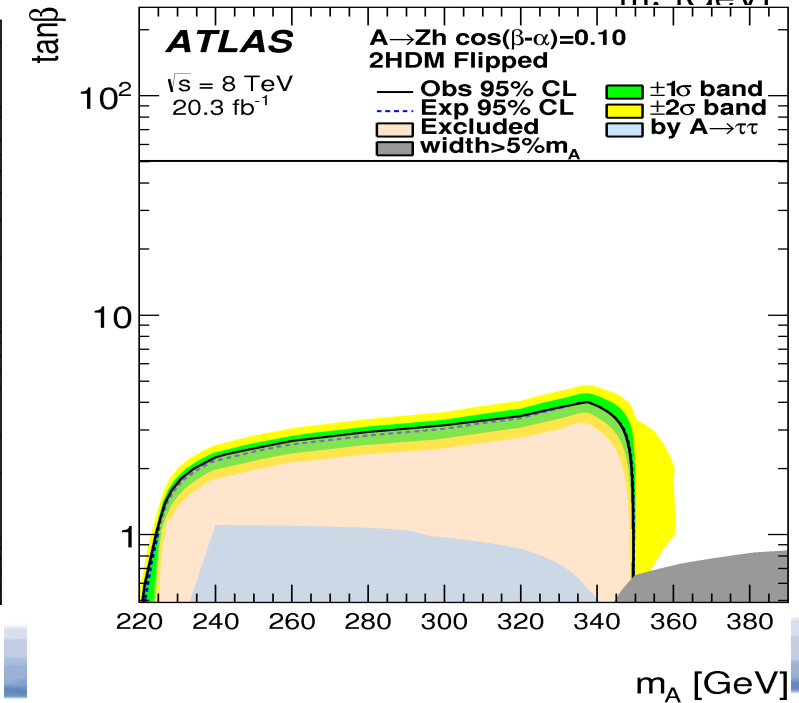


Search for A → Zh: 2HDM interpretations









Assumptions:

$$m_A = m_H = m_{H^\pm}$$
$$m_h = 125\,GeV$$
$$m_{12}^2 = \frac{m_A^2 \tan\beta}{(1+\tan^2\beta)}$$
$$\cos(\beta-\alpha) = 0.1$$

Blue shaded area denotes previous A → ττ searches excluded regions.