Searches for Additional Higgs Bosons in Extensions of the Standard Model at ATLAS

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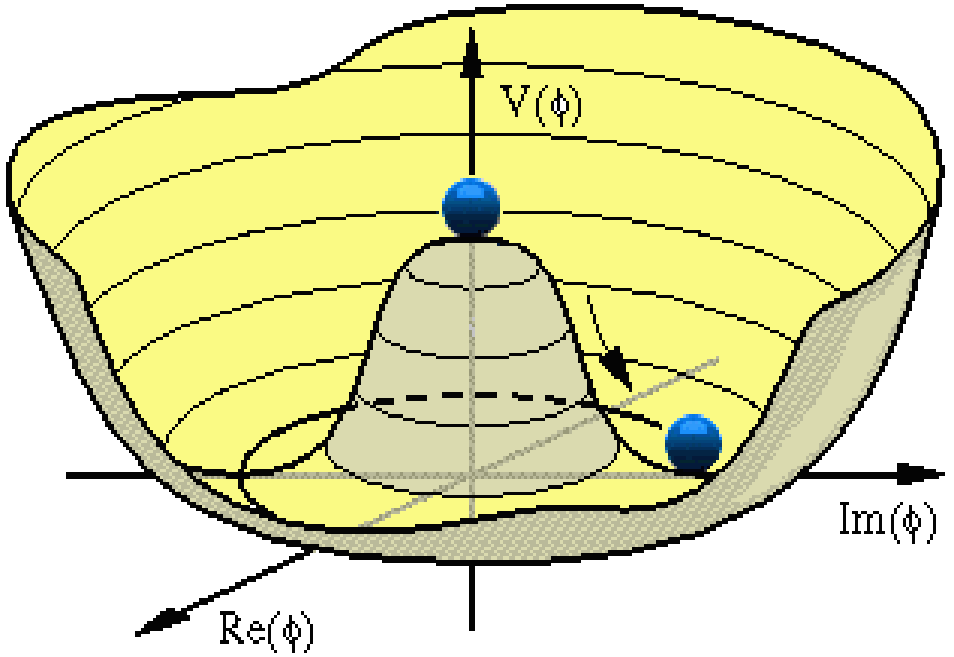
Spontaneous Symmetry Breaking of Gauge Symmetry

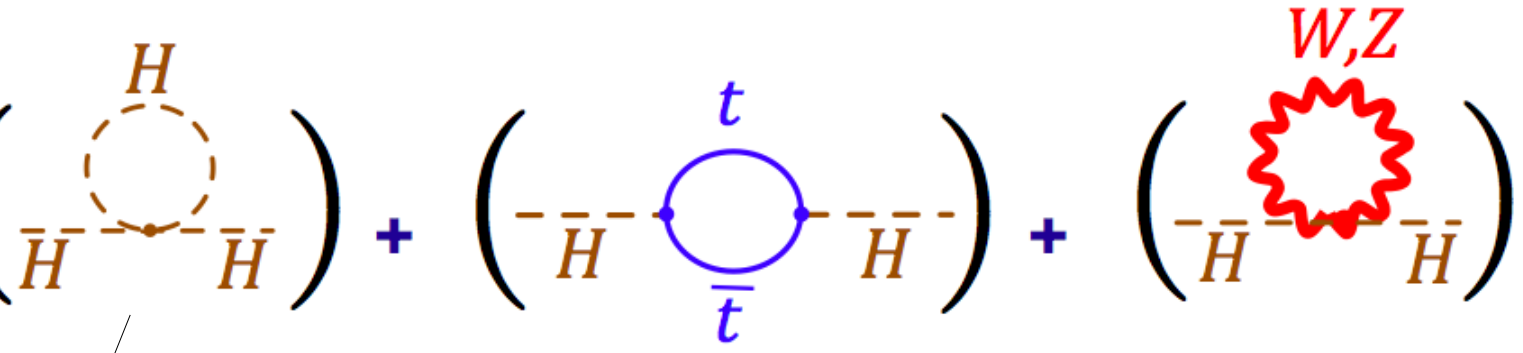
- The Higgs potential in the SM is a parameterization that respects certain rules of QFT



- Phase transition → vacuum state possesses non-trivial quantum numbers
  - Dynamical origin of this phase transition is not known
  - Implies vacuum is a condensed, superconductor-like state

- Discovery of the "radial excitation" a.k.a the Higgs boson means that we have taken the first, big step in establishing the properties of this potential

Next Big Question: Why is the Higgs Boson so Light?

$$m_H^2 - m_{\text{bare}}^2 =$$ 

$$\lambda \int^{\Lambda} d^4k \, (k^2 - m_H^{\,2})^{-1} \sim \Lambda^2 \lambda$$

The Higgs boson ought to be a very heavy particle, naturally

However, observed $m_H << \Lambda$

Higgs Bosons in Extensions of Standard Model

- Searches based on three classes of models:
  - Another "SM-like Higgs boson" at a different mass
  - Another Neutral Higgs Boson at a different mass
    - 125 GeV Higgs boson will have non-SM properties
  - Charged Higgs Bosons

- Benchmark models
  - Two-Higgs Doublet Models (2HDM)
    - Can contain additional CP-violating terms and facilitate matter-antimatter asymmetry in the early universe
  - MSSM and next-to-MSSM (NMSSM) contain specific incarnations of 2HDM

SM-like Higgs Boson at High Mass

"Search for a high-mass Higgs boson in the H→WW→lνlν decay channel with the ATLAS detector using 21 fb^{-1} of proton-proton collision data"
[ATLAS-CONF-2013-067]

gluon-gluon fusion and vector-boson fusion modes both included in data interpretation

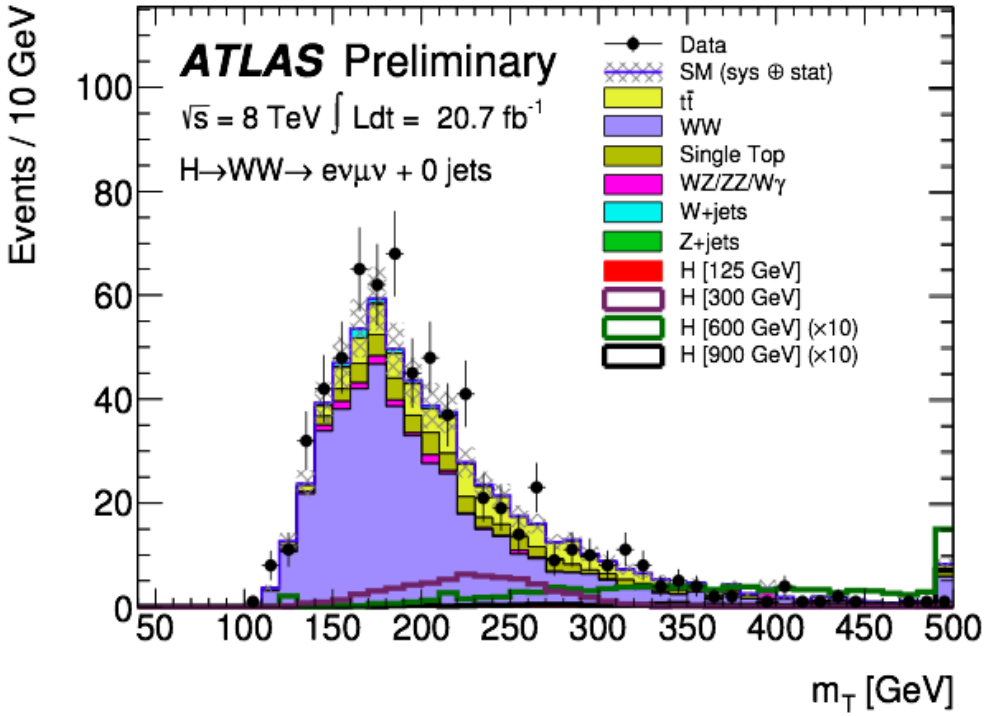
- Analysis of data using
  - SM-like Higgs interpretation at high mass
    - Width growing with mass as in SM
    - Above 400 GeV, interference with non-resonant WW production important (included using re-weighting)
  - Narrow-width approximation
    - Fixed 1 GeV width BW lineshape
- H → WW → *e* + μ + missing E_T channel used since it dominates sensitivity

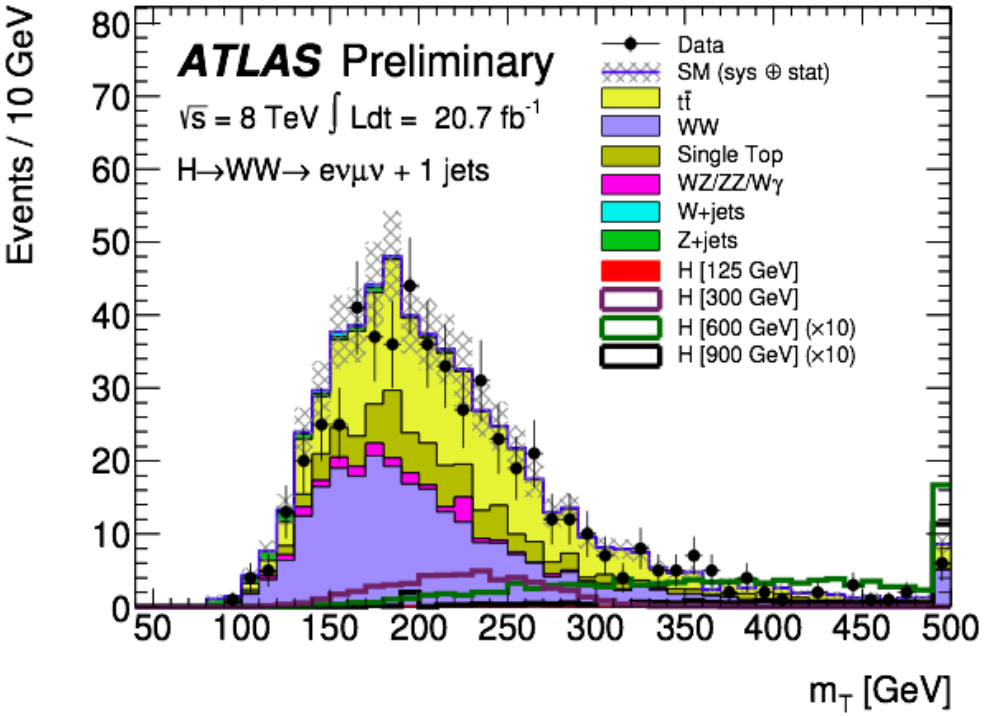
SM-like Higgs Boson at High Mass

- Object and Event Selection

Category	0-jet	1-jet	>=2-jet
Preselection	An isolated electron and an isolated muon, with opposite charge, each with $p_T > 40$ GeV, $m_{\ell\ell} > 10$ GeV		
Missing transverse momentum	$E_{T,rel}^{miss} > 25$ GeV	$E_{T,rel}^{miss} > 25$ GeV	$E_T^{miss} > 20$ GeV
General selection	- $\Delta\phi_{\ell\ell,E_T^{miss}} > \pi/2$ $p_T^{\ell\ell} > 30$ GeV	$N_{b\text{-jet}} = 0$ - $Z/\gamma^* \to \tau\tau$ veto	$N_{b\text{-jet}} = 0$ $p_T^{tot} < 45$ GeV $Z/\gamma^* \to \tau\tau$ veto
VBF topology	- - - -	- - - -	$m_{jj} > 500$ GeV $\lvert\Delta y_{jj}\rvert > 2.8$ No jets ($p_T > 20$ GeV) in the rapidity gap; require both ℓ in the rapidity gap
$H \to WW \to \ell\nu\ell\nu$ topology	$m_{\ell\ell} > 50$ GeV $\Delta\eta_{\ell\ell} < 1.0$	$m_{\ell\ell} > 50$ GeV $\Delta\eta_{\ell\ell} < 1.0$	$m_{\ell\ell} > 50$ GeV $\Delta\eta_{\ell\ell} < 1.0$

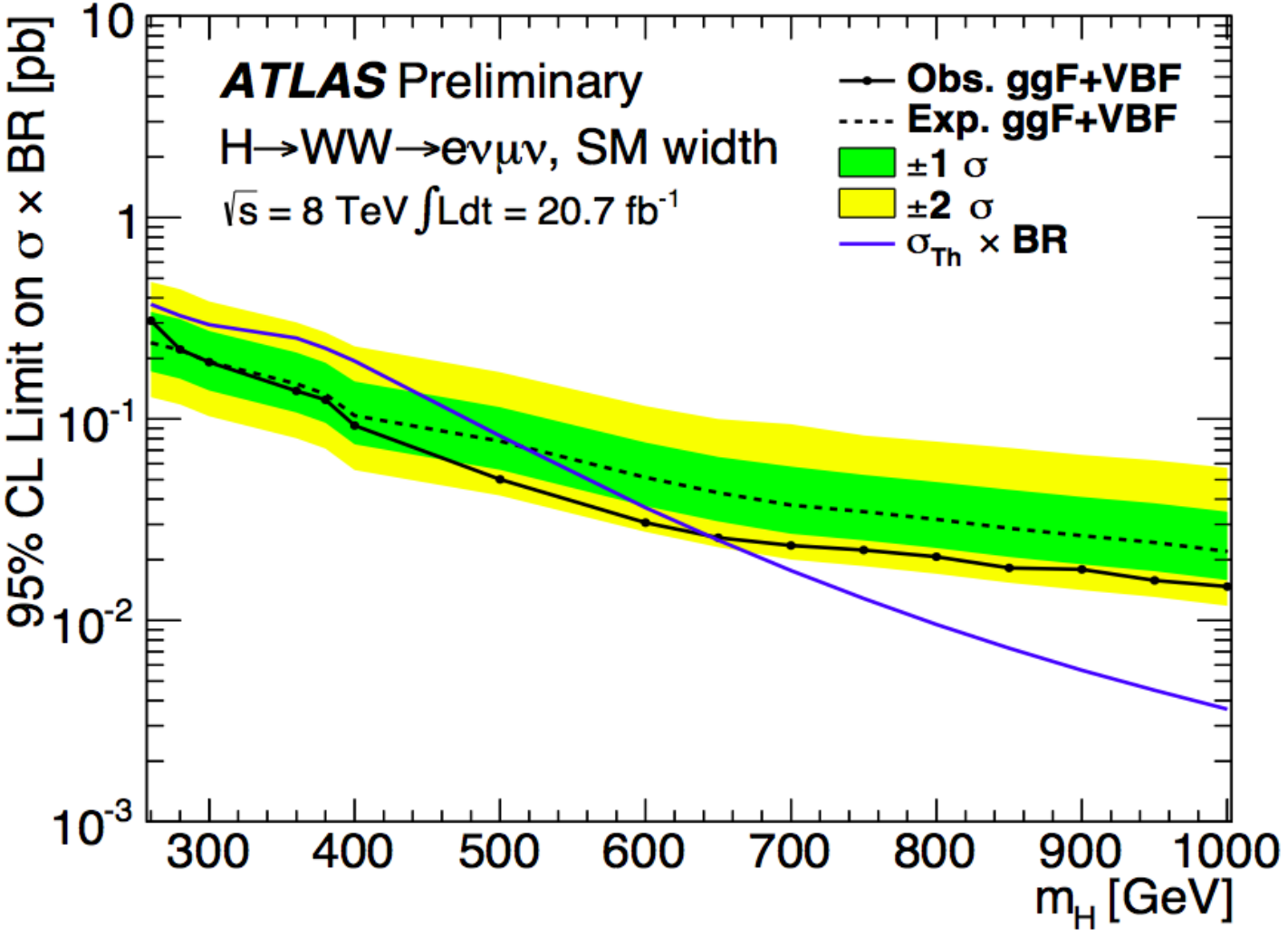
- Dilepton transverse mass distributions after all selection





SM-like Higgs Boson at High Mass

- Exclusion of a Higgs boson with SM-like production and couplings, in the mass range [260, 642] GeV



Neutral Heavy H → WW with Narrow Width

- eg. in 2HDM, gauge bosons couple to two Higgs doublets
  - More terms in the Higgs potential
  - Mass parameter can be separated from quartic self-coupling, allowing heavy Higgs to be narrow
  - Line-shape model: fixed 1 GeV Breit-Wigner
    - Negligible interference with non-resonant WW production

Results: $\sigma \times BR(H \rightarrow WW) <$
230 fb for m = 300 GeV
32 fb for m = 600 GeV
29 fb for m = 1 TeV.

Neutral Higgs Bosons with Non-SM Properties

"Search for flavour changing neutral currents in top quark decays $t \to cH$, with $H \to \gamma\gamma$, and limit on the tcH coupling with the ATLAS detector at the LHC"
[ATLAS-CONF-2013-081]

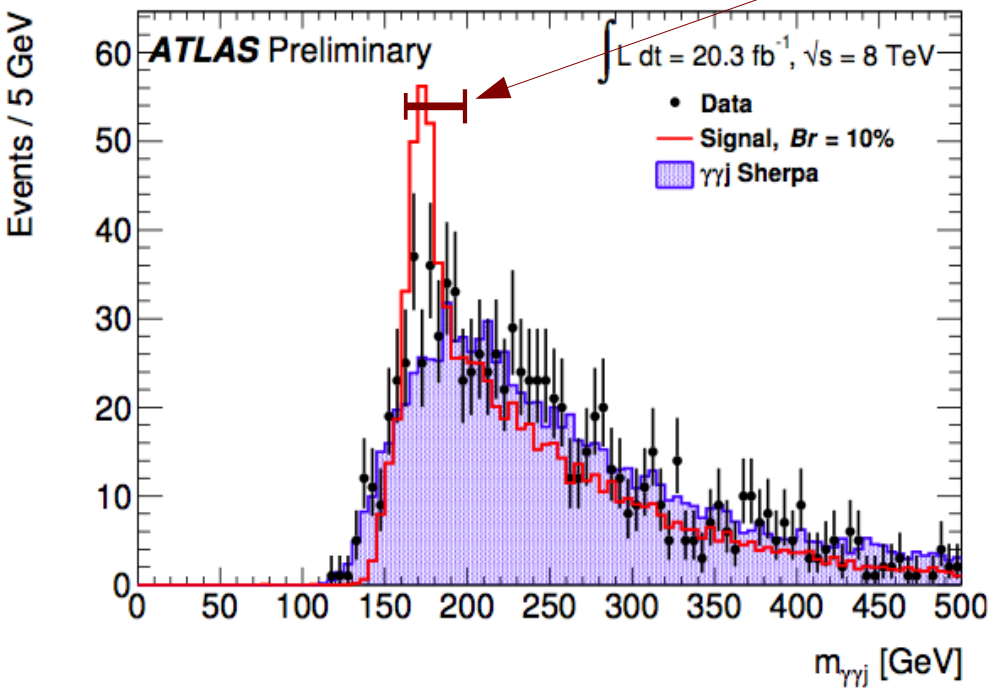
(QS = quark singlet
FC = flavor conserving)

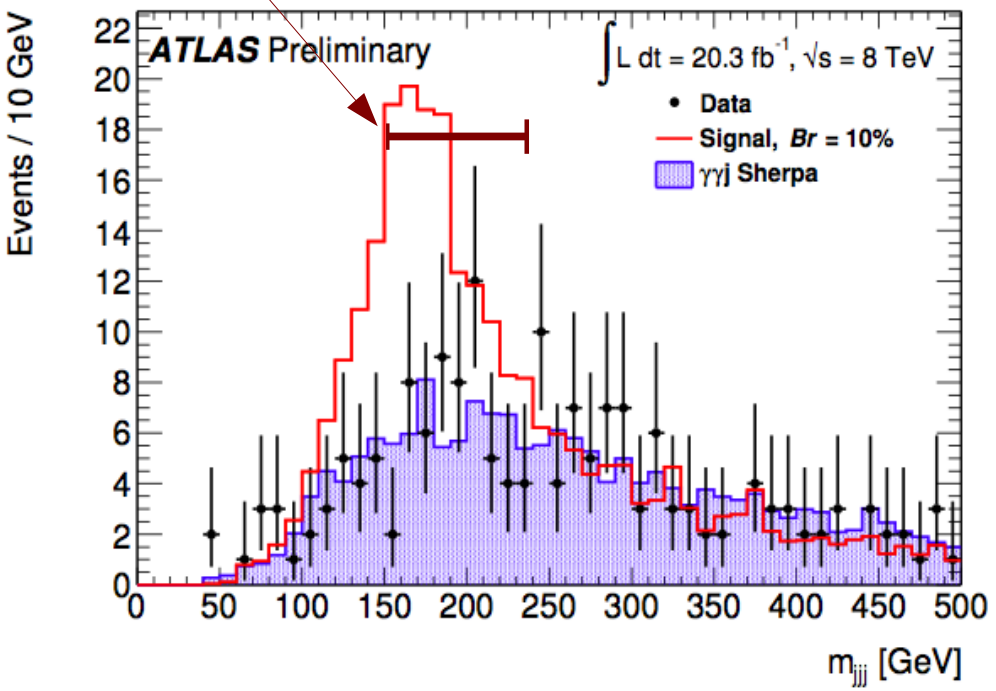
Process	SM	QS	2HDM-III	FC-2HDM	MSSM
$t \to u\gamma$	$3.7 \cdot 10^{-16}$	$7.5 \cdot 10^{-9}$	—	—	$2 \cdot 10^{-6}$
$t \to uZ$	$8 \cdot 10^{-17}$	$1.1 \cdot 10^{-4}$	—	—	$2 \cdot 10^{-6}$
$t \to uH$	$2 \cdot 10^{-17}$	$4.1 \cdot 10^{-5}$	$5.5 \cdot 10^{-6}$	—	10^{-5}
$t \to c\gamma$	$4.6 \cdot 10^{-14}$	$7.5 \cdot 10^{-9}$	$\sim 10^{-6}$	$\sim 10^{-9}$	$2 \cdot 10^{-6}$
$t \to cZ$	$1 \cdot 10^{-14}$	$1.1 \cdot 10^{-4}$	$\sim 10^{-7}$	$\sim 10^{-10}$	$2 \cdot 10^{-6}$
$t \to cH$	$3 \cdot 10^{-15}$	$4.1 \cdot 10^{-5}$	$1.5 \cdot 10^{-3}$	$\sim 10^{-5}$	10^{-5}

$t \to c\mathrm{H} \to c\gamma\gamma$

Top mass cuts

$t \to b\mathrm{W} \to bjj$

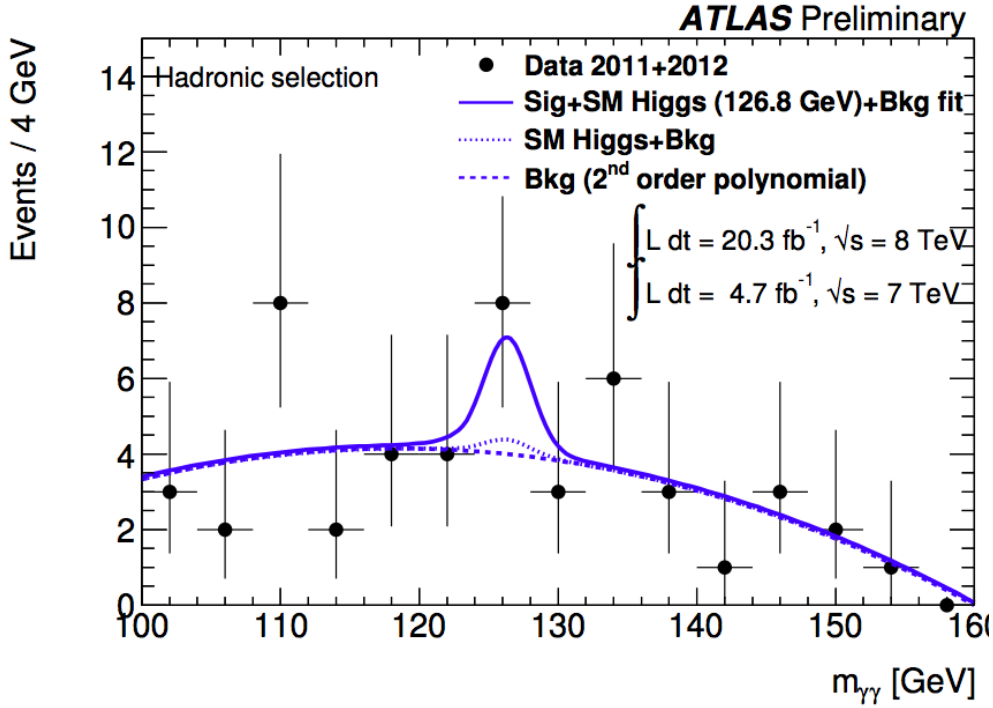


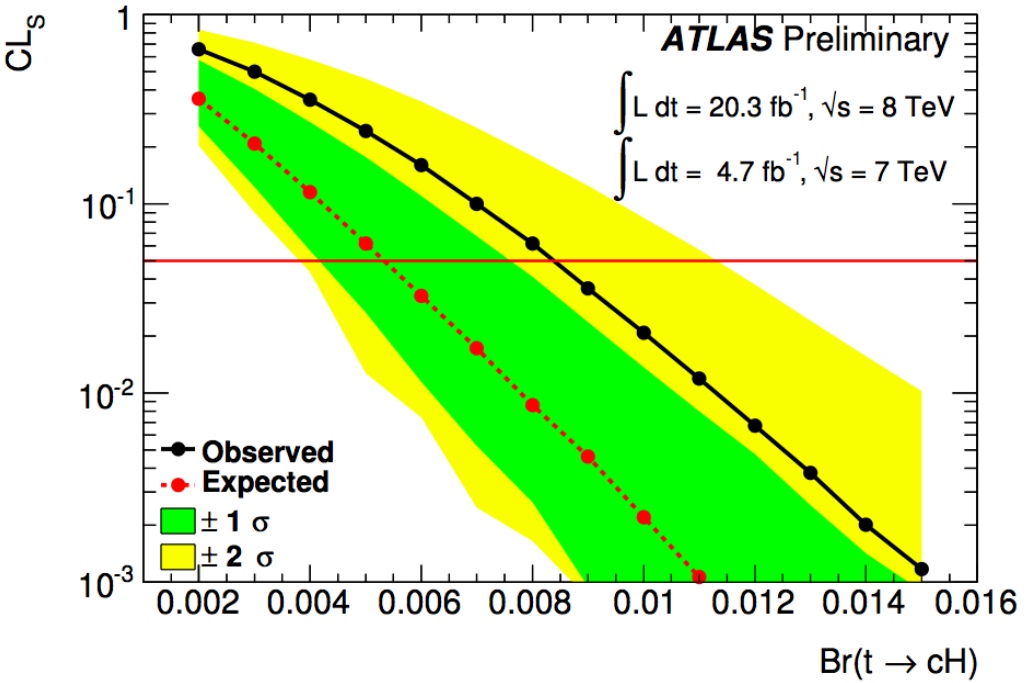


Neutral Higgs Bosons with Non-SM Properties

"Search for flavour changing neutral currents in top quark decays $t \rightarrow cH$, with $H \rightarrow \gamma\gamma$, and limit on the tcH coupling with the ATLAS detector at the LHC"
[ATLAS-CONF-2013-081]

- Look for Higgs in diphoton mass spectrum
  - Model background shape with *SHERPA*



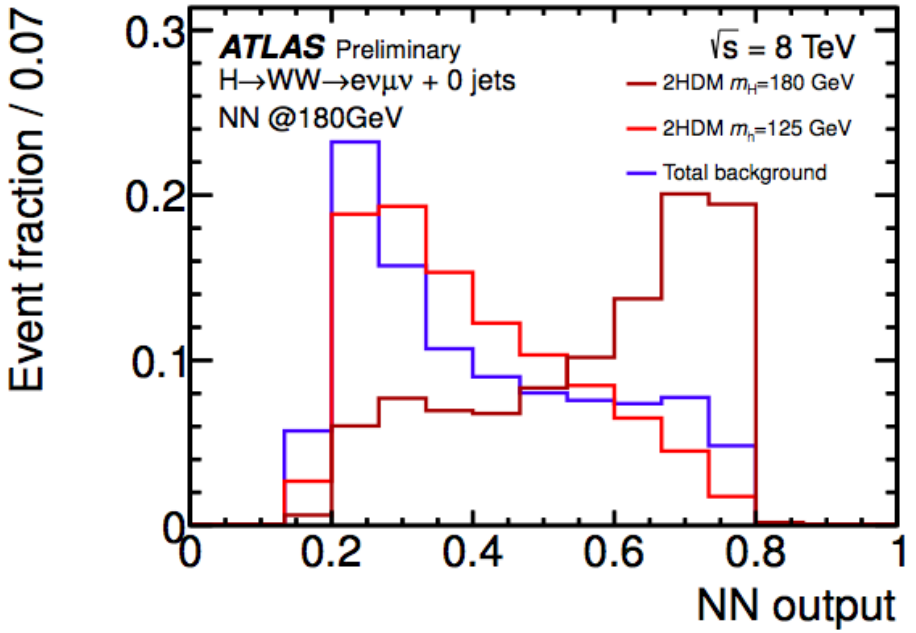


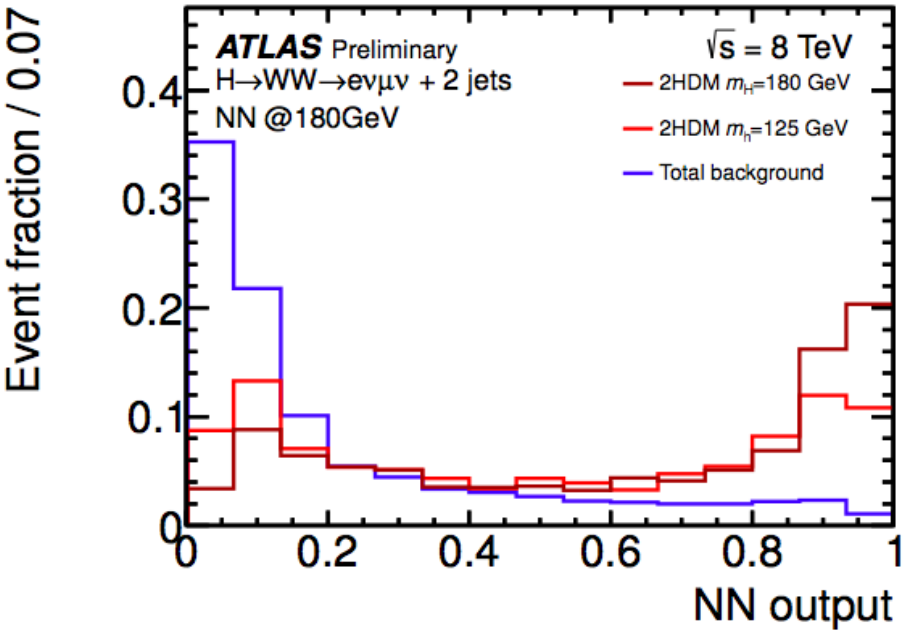
BR(t → cH) < 0.83% (observed) at 95% CL (< 0.53 % expected for SM)

Neutral Higgs Bosons with Non-SM Properties

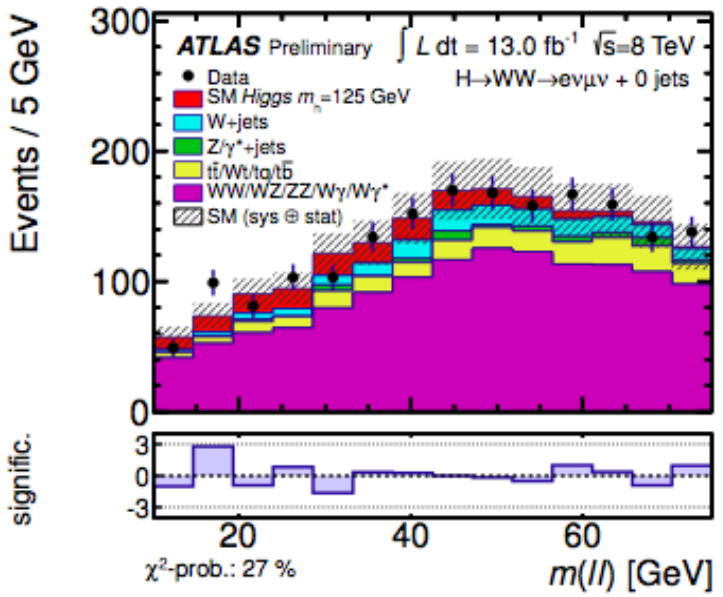
"Search for Higgs bosons in Two-Higgs-Doublet models in the $H \to WW \to e\nu\mu\nu$ channel with the ATLAS detector" [ATLAS-CONF-2013-027]

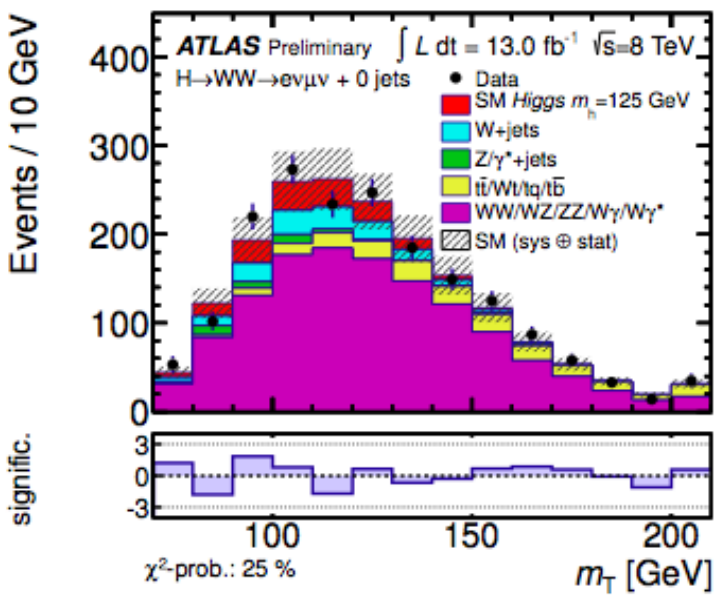
- Simultaneous fit for light Higgs boson @125 GeV and heavy, CP-even Higgs boson
  - Mixing angle α between these two CP-even states in 2HDM
- Multivariate Neural Network (NeuroBayes) used to increase sensitivity in the search region [135, 300] GeV of the heavy Higgs mass
- Gluon-gluon fusion and vector-boson fusion modes analyzed separately in 0-jet and 2-jet bins respectively



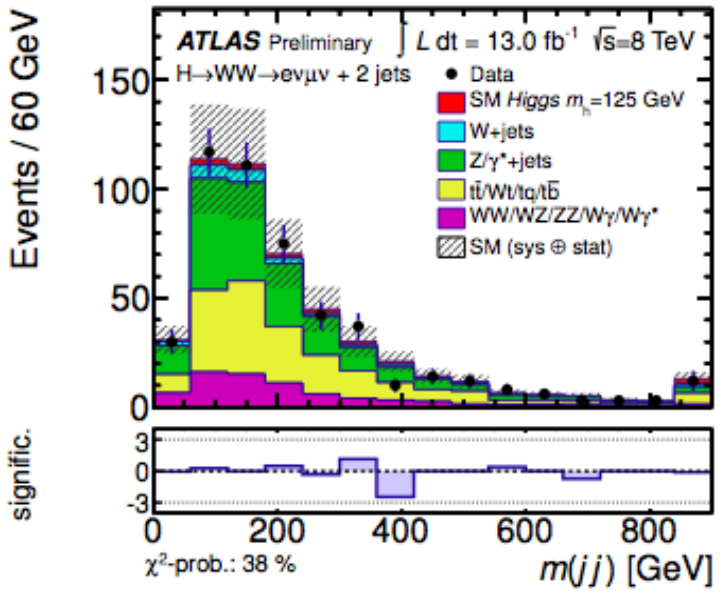


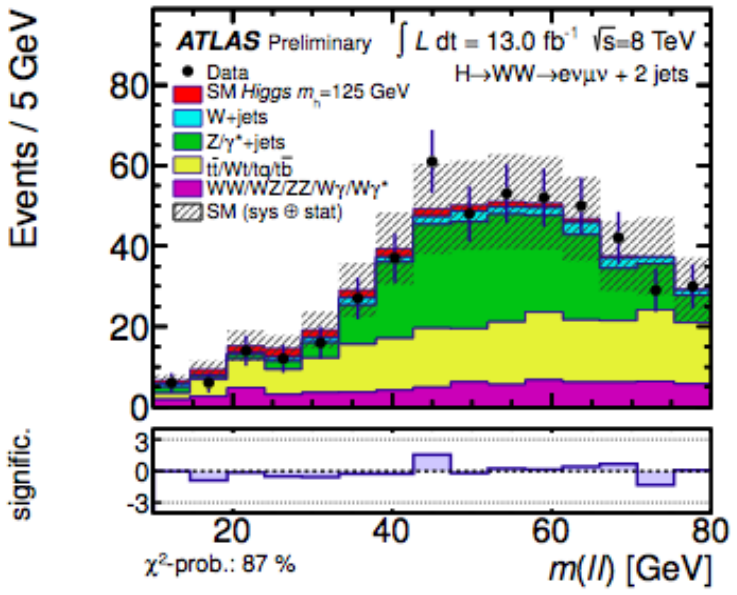
Heavy Neutral Higgs Boson in 2HDM





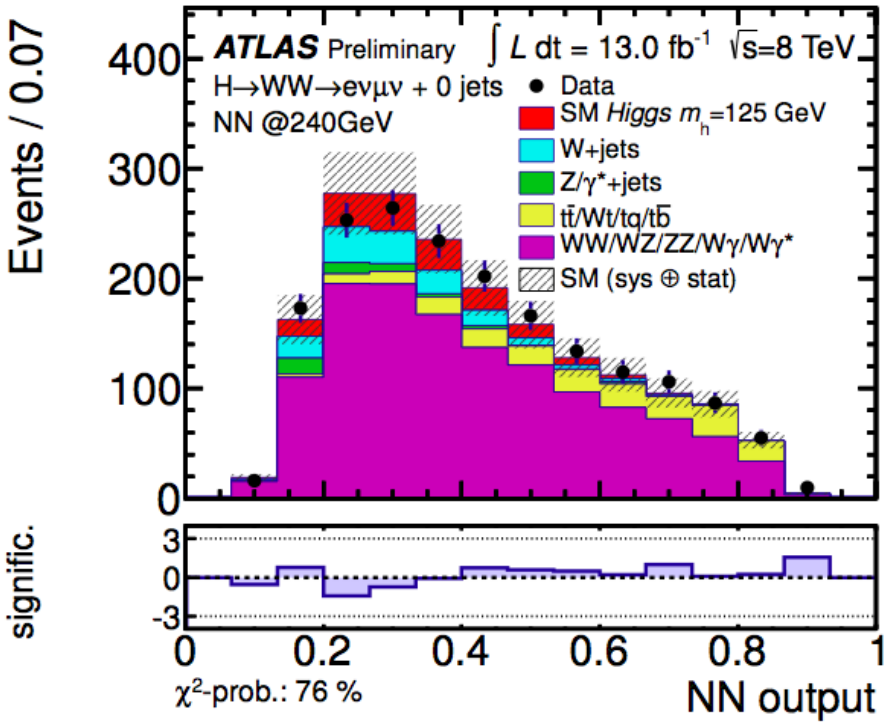
Signal-region distributions of most sensitive input distributions to NN for 0-jet bin (top) and 2-jet bin (bottom)



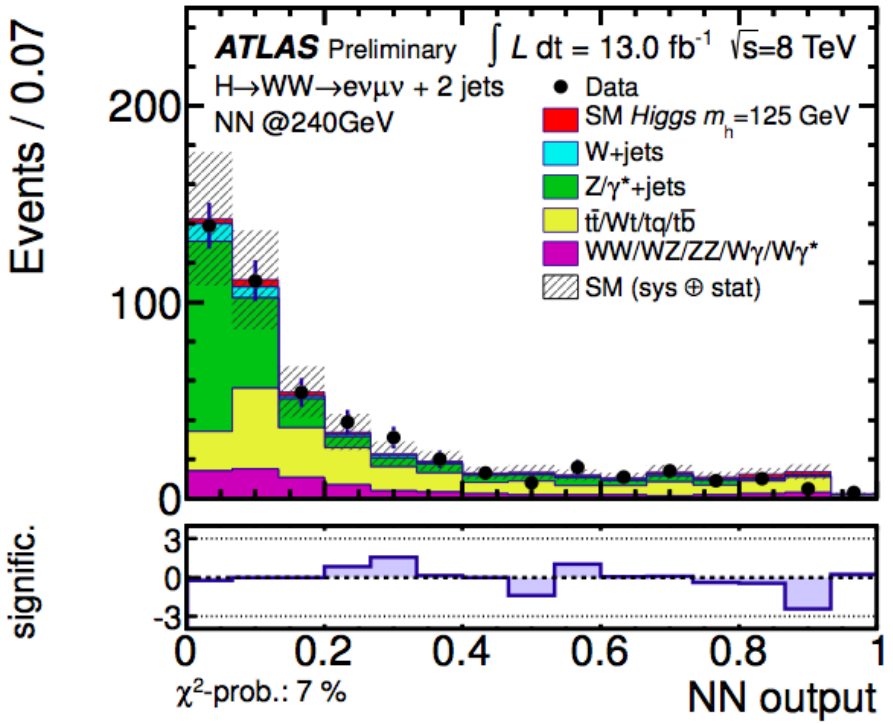


Heavy Neutral Higgs Boson in 2HDM

0-jet bin

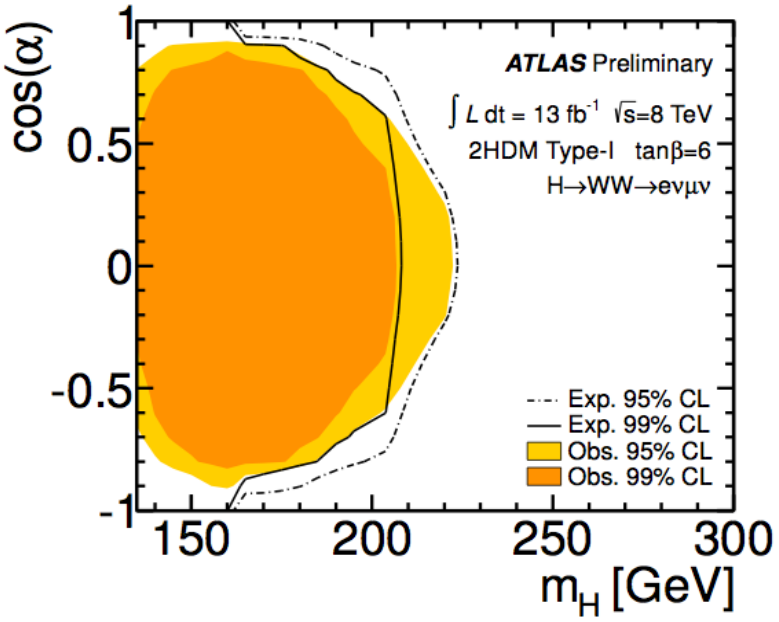


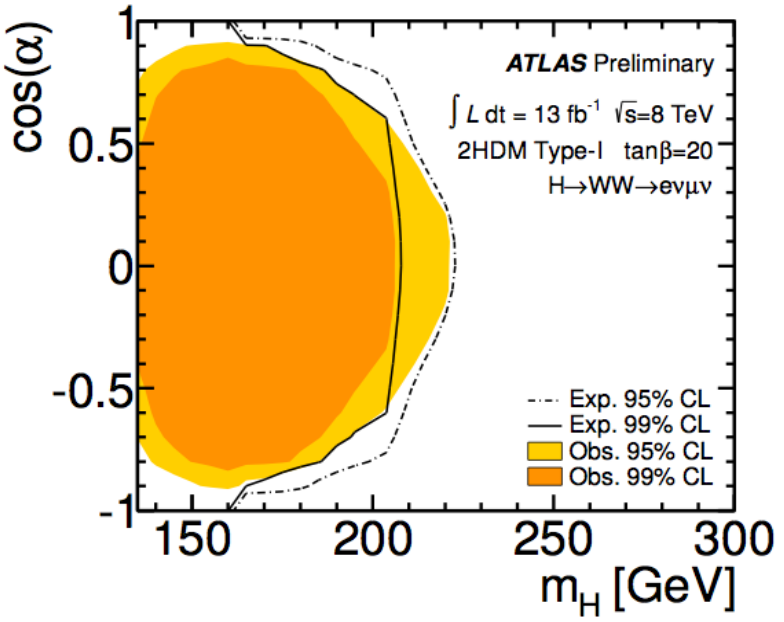
2-jet bin



Signal-region distributions of NN discriminant

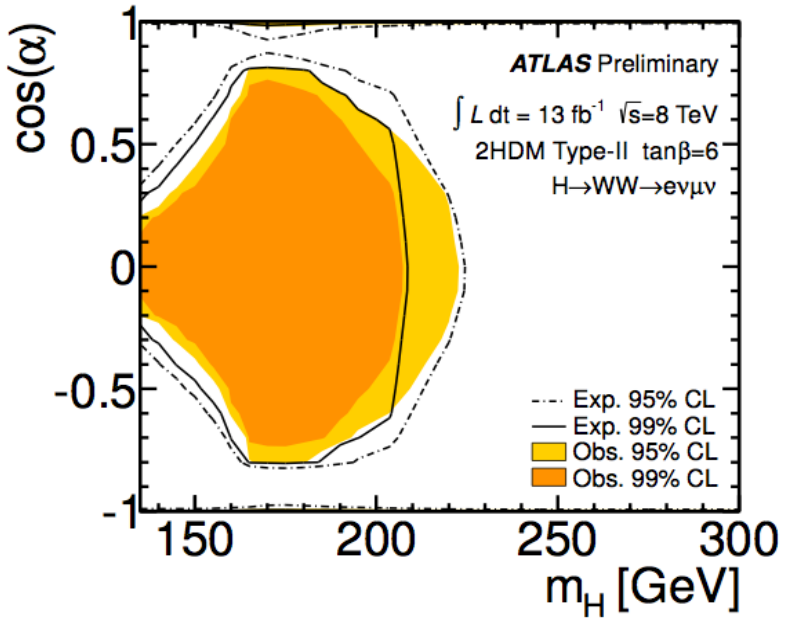
Heavy Neutral Higgs Boson in 2HDM

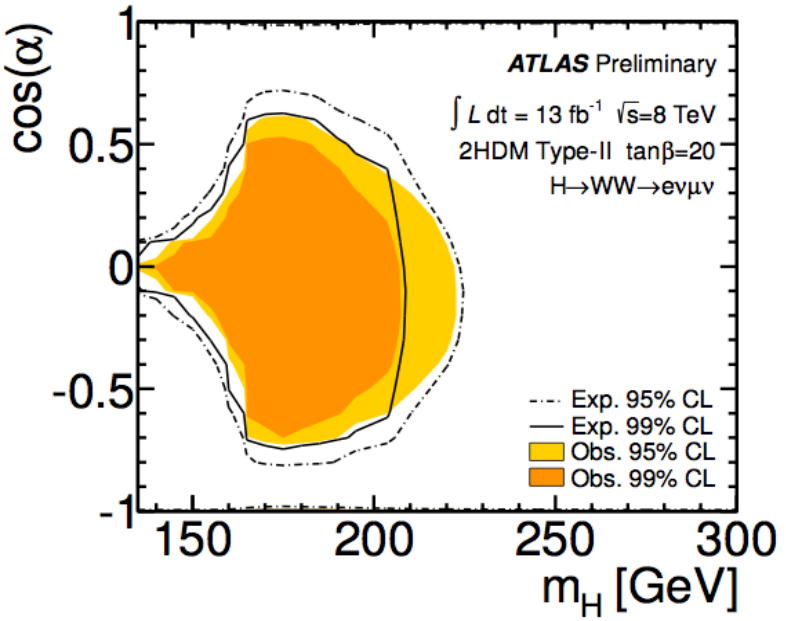




Exclusion regions in the $\cos(\alpha)$ – m_H plane for different tan β values

type I model (top) and type II model (bottom)





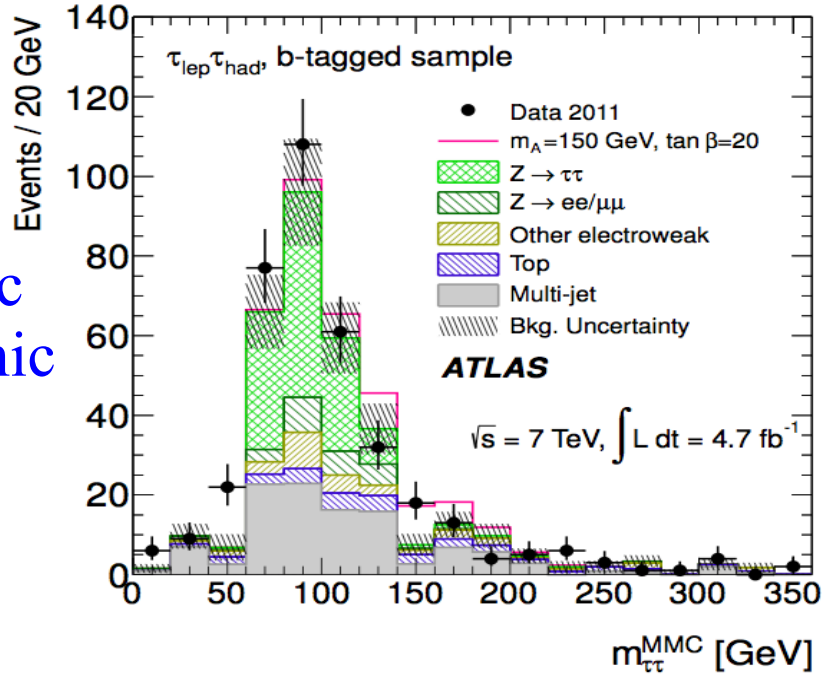
Neutral Higgs Bosons with Non-SM Properties

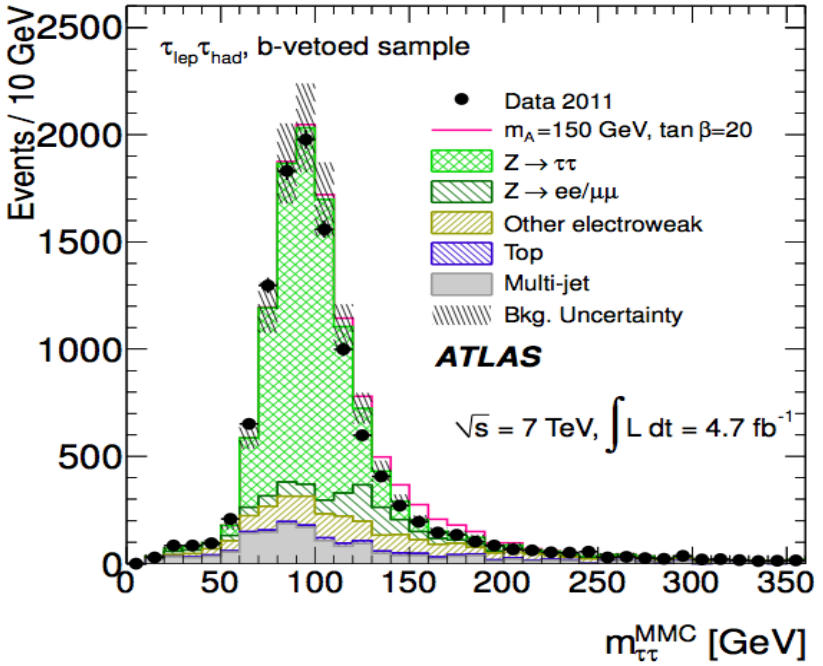
"Search for the neutral Higgs bosons of the Minimal Supersymmetric Standard Model in pp collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector" [JHEP 02 (2013) 095]

- Search dimuon and ditau decay channels of Higgs bosons
- Simultaneously include light (h) and heavy (H) CP-even, and CP-odd (A) Higgs bosons in signal templates
- Tau-embedding in Drell-Yan (μμ) data used to understand τ efficiencies and backgrounds
- Missing-mass calculation used to reconstruct ditau invariant mass
- Flavor separation into one-*b*-tagged and zero-*b*-tagged samples since *b* quark-induced production is favored at high tan β

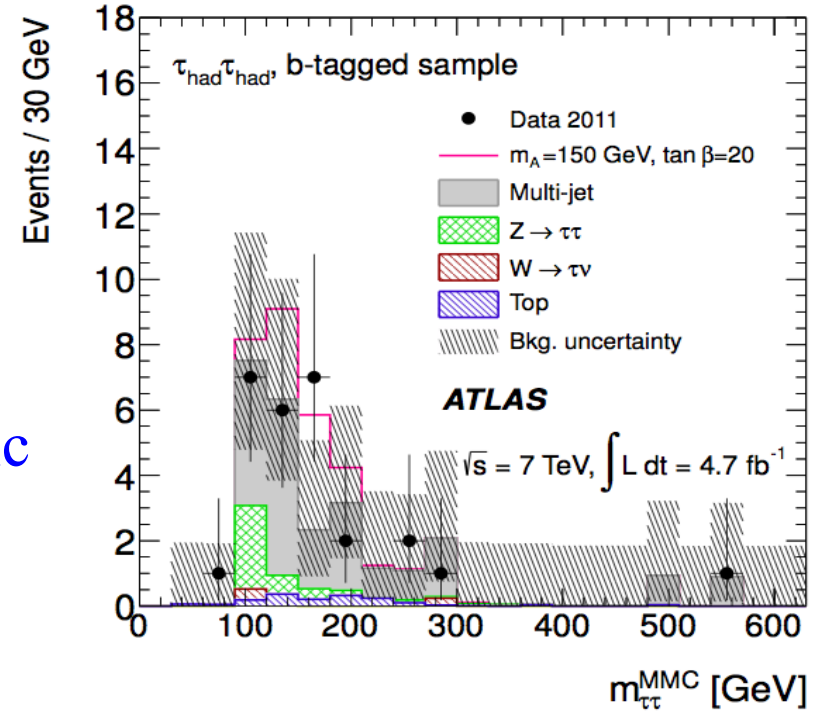
Neutral Higgs Bosons in the MSSM

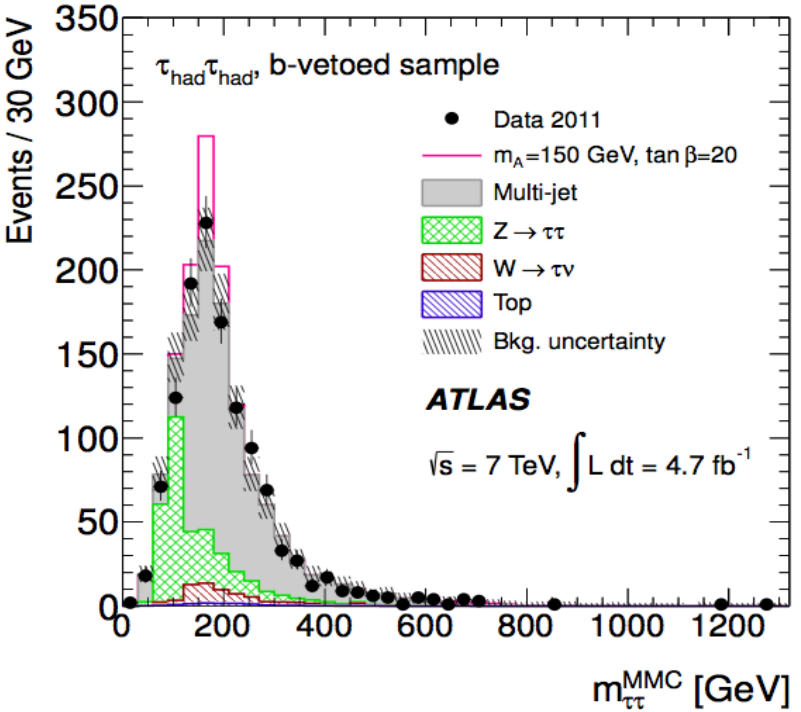
Leptonic +hadronic taus



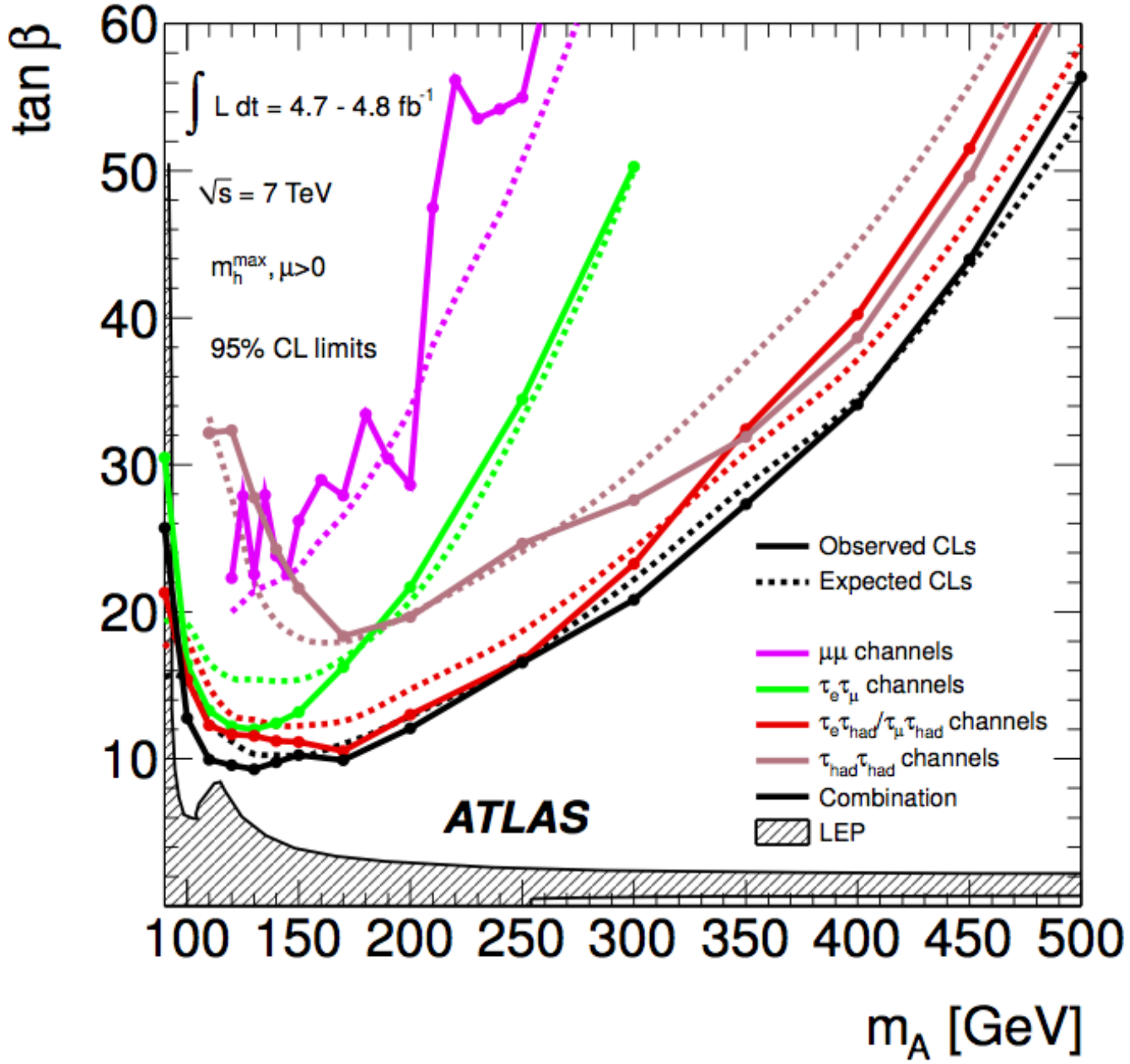


Two hadronic taus





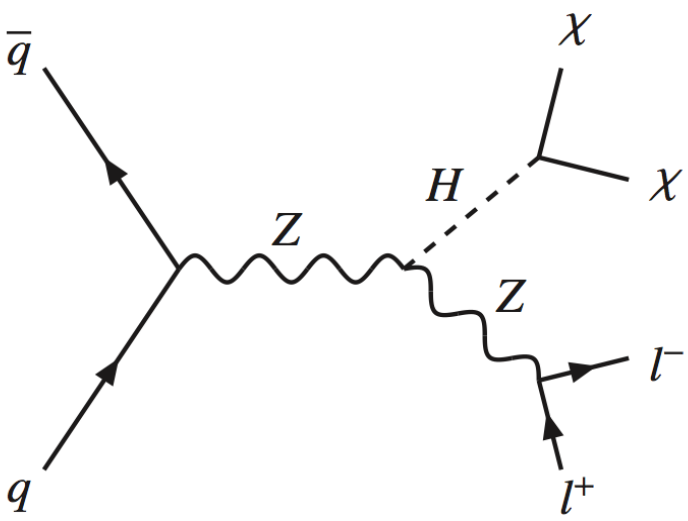
Neutral Higgs Bosons in the MSSM

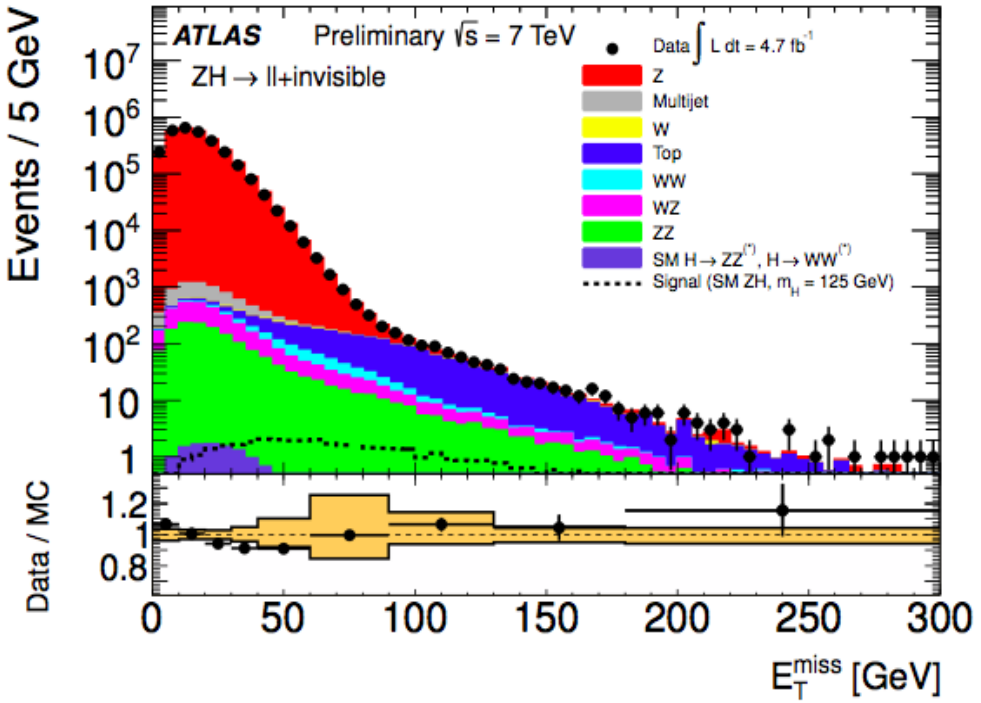


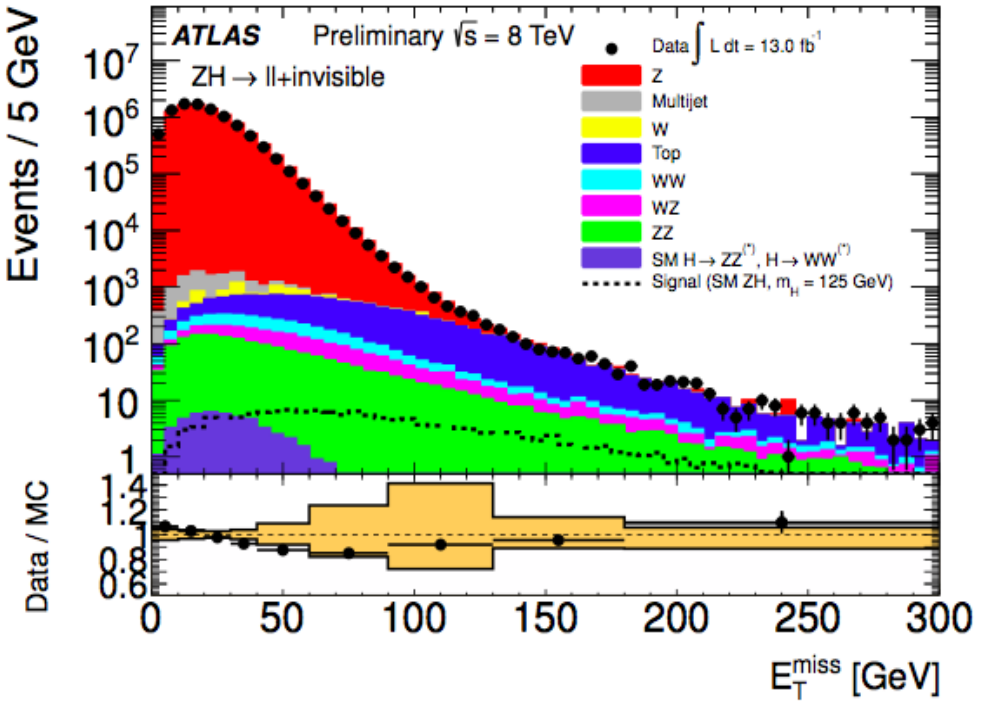
Neutral Higgs Boson with Invisible Decays

"Search for invisible decays of a Higgs boson produced in association with a Z boson in ATLAS" [ATLAS-CONF-2013-011]

Constrain invisible decays of the Higgs boson and additional Higgs bosons decaying invisibly

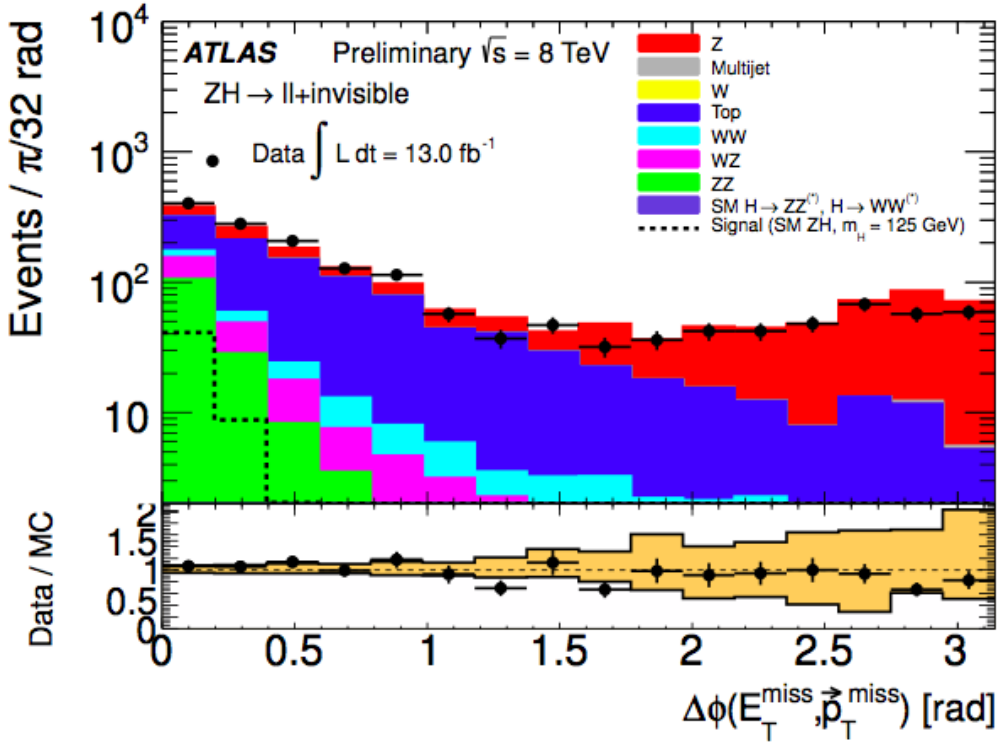


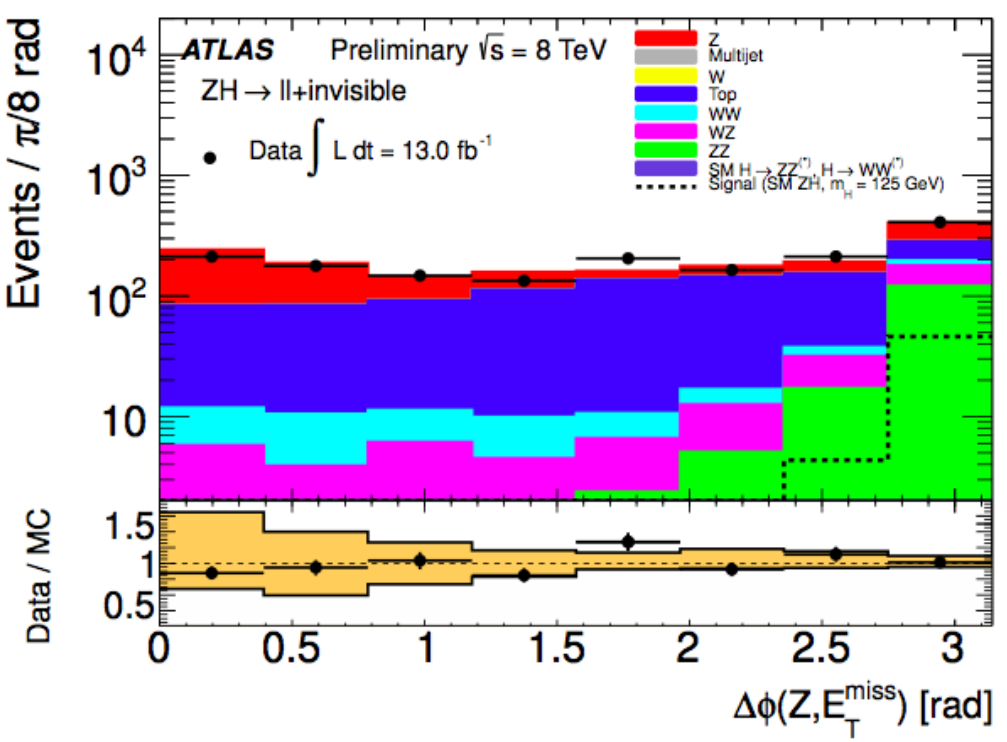




Neutral Higgs Boson with Invisible Decays

"Search for invisible decays of a Higgs boson produced in association with a Z boson in ATLAS" [ATLAS-CONF-2013-011]





Comparison of missing-p_T azimuth from calorimeter and tracks

selection cut

Neutral Higgs Boson with Invisible Decays

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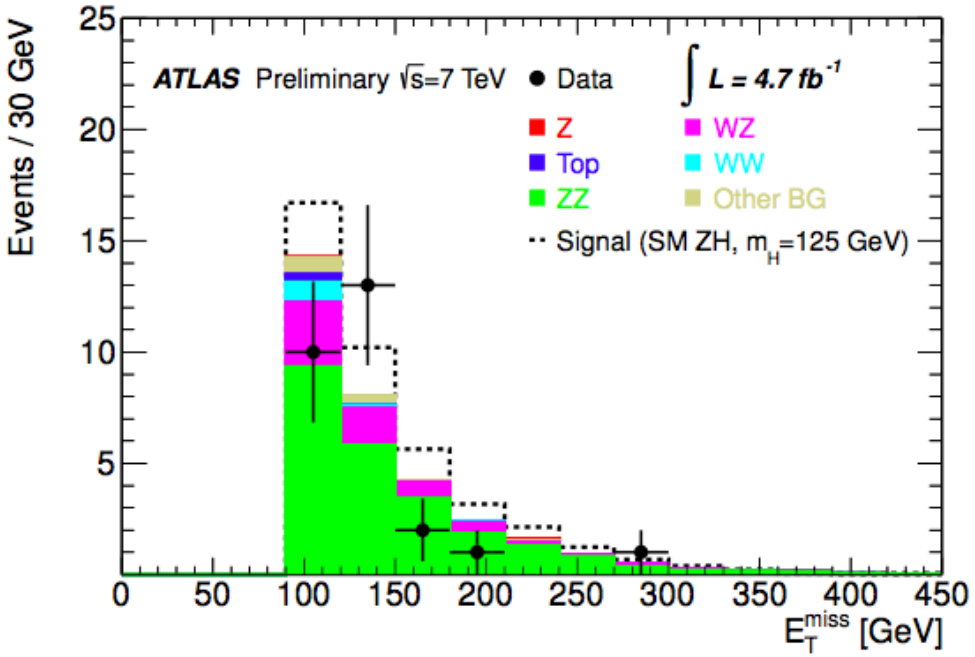
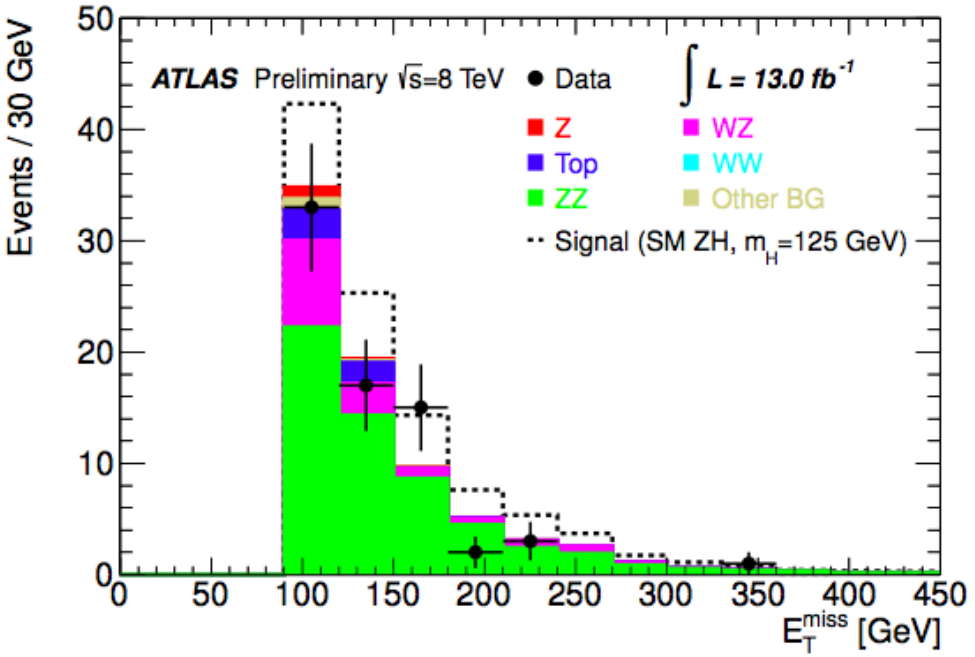
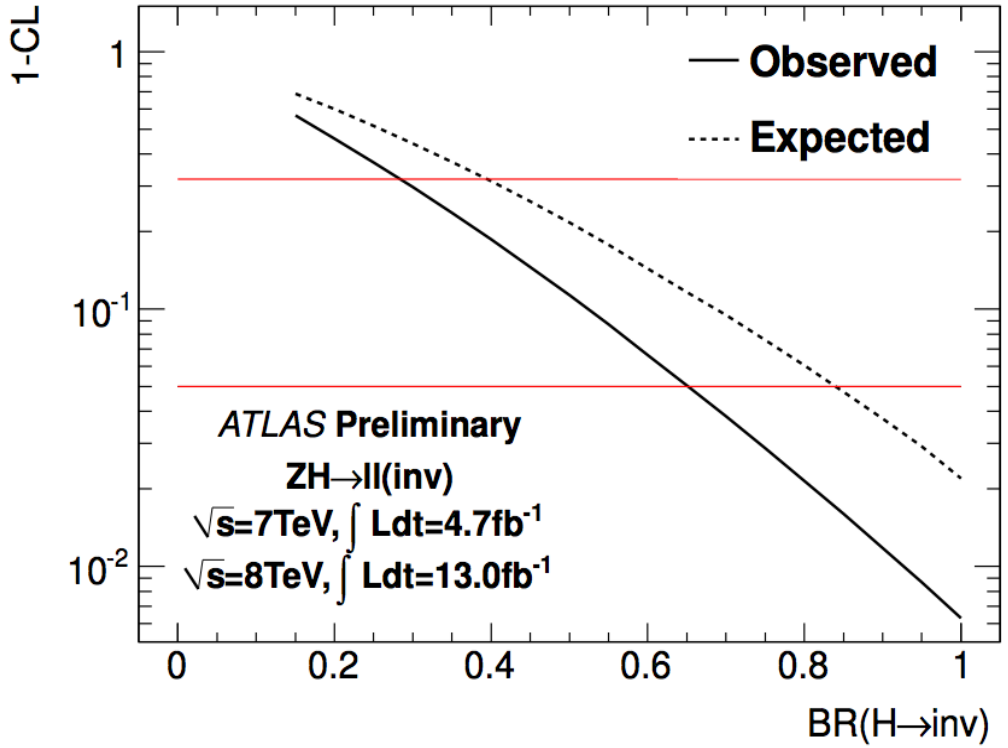




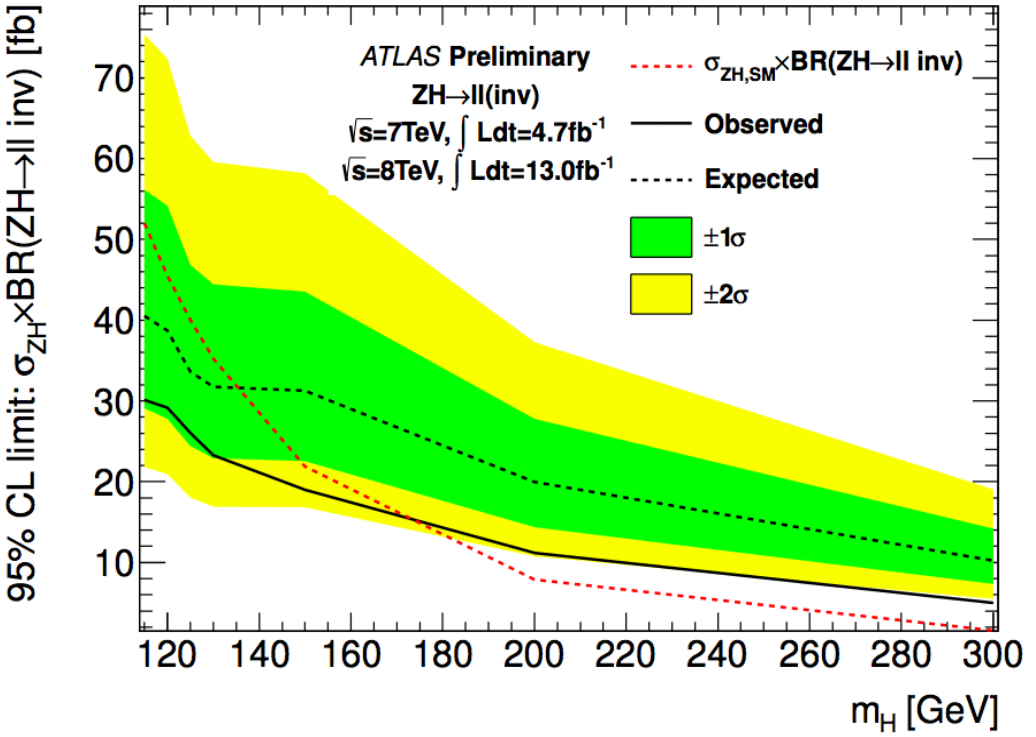
signal model: BR(SM H → invisible) = 100%

Neutral Higgs Boson with Invisible Decays

"Search for invisible decays of a Higgs boson produced in association with a Z boson in ATLAS" [ATLAS-CONF-2013-011]



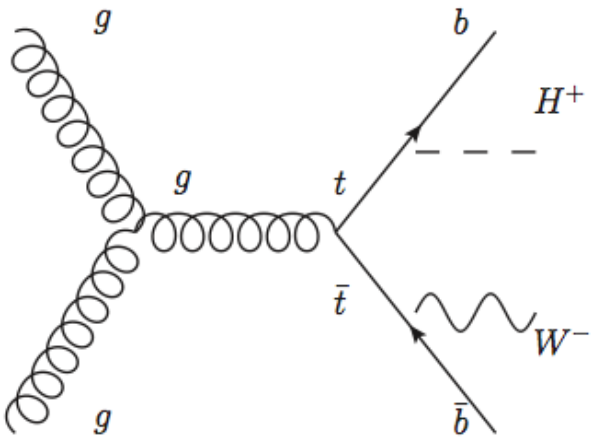
Limits on BR (H_{SM} → inv)

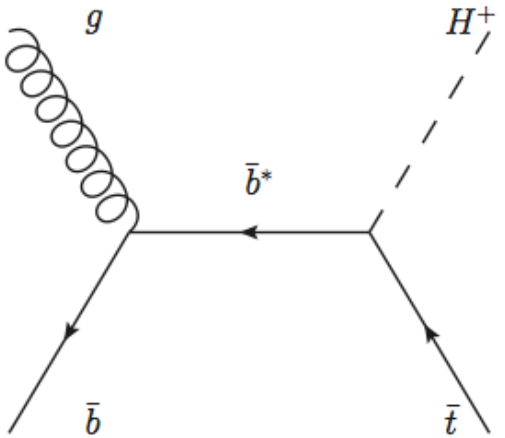


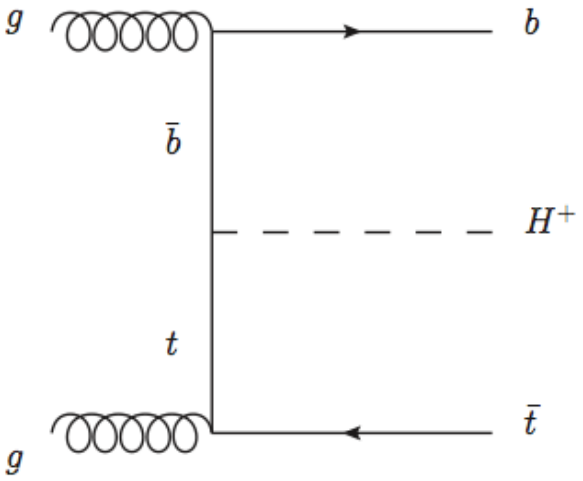
Limits on heavy SM-like H → inv

Charged Higgs

"Search for charged Higgs bosons in the τ+jets final state with pp collision data recorded at √s=8 TeV with the ATLAS experiment" [ATLAS-CONF-2013-090]







light H^+ from top decay

heavy H^+, associated production

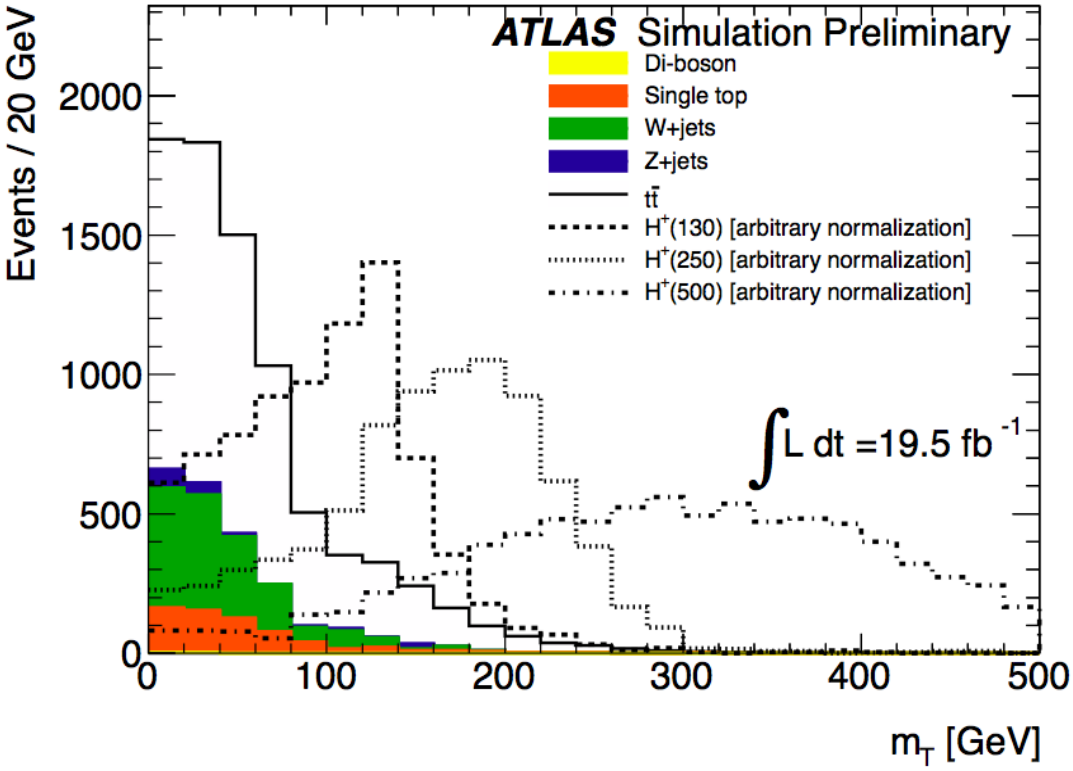
Search in $H^+ \rightarrow \tau + \nu$ decay channel, motivated by MSSM when $\tan\beta > 3$

Charged Higgs

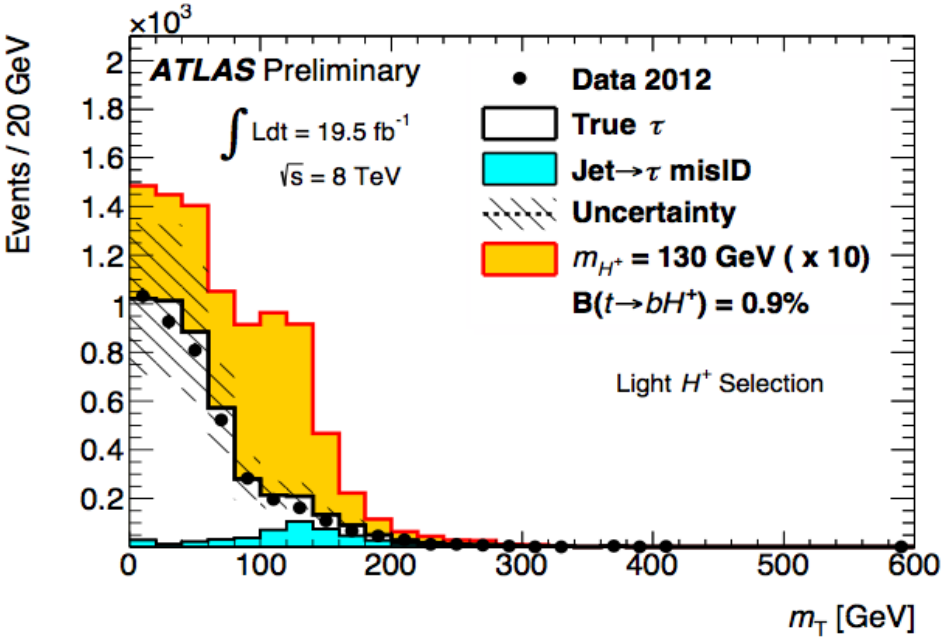
"Search for charged Higgs bosons in the τ+jets final state with pp collision data recorded at √s=8 TeV with the ATLAS experiment" [ATLAS-CONF-2013-090]

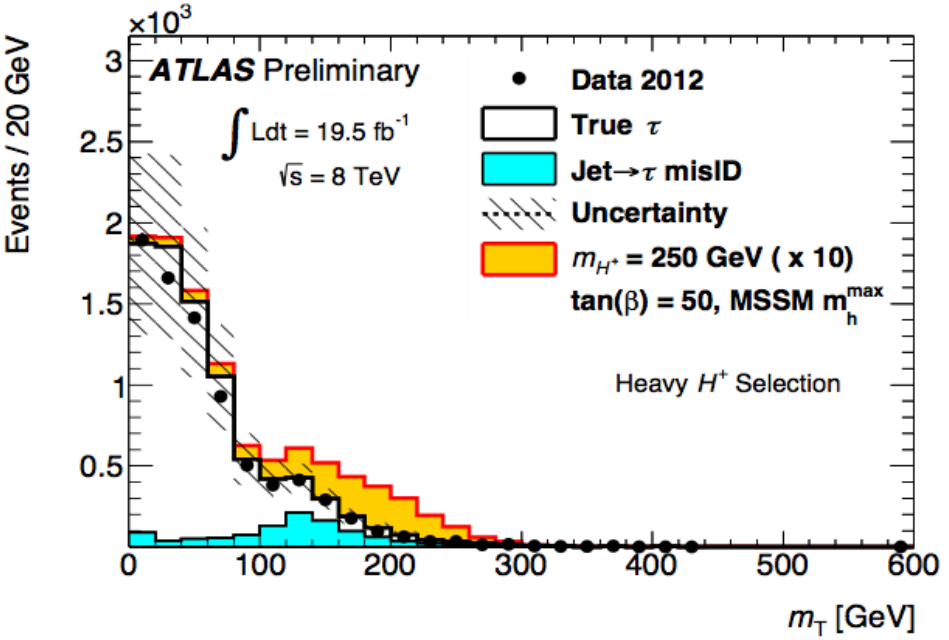
- Fully-hadronic decay of other top quark required
- Hadronic decay of τ lepton selected using BDT algorithm
- Transverse mass distribution of τ + missing E_T shows characteristic Jacobian edge from H^+ decay

Missing E_T > 65 (80) GeV
for light (heavy) H^+ search



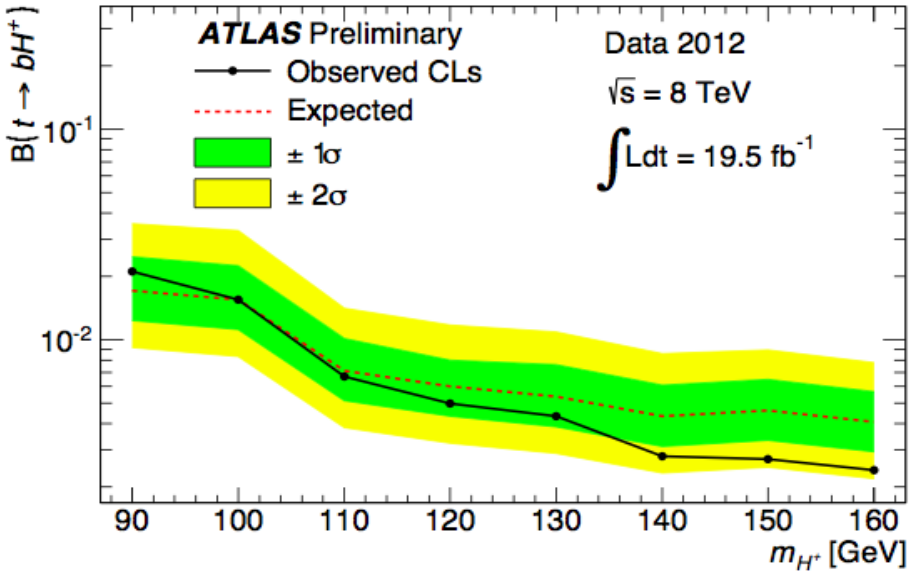
Charged Higgs

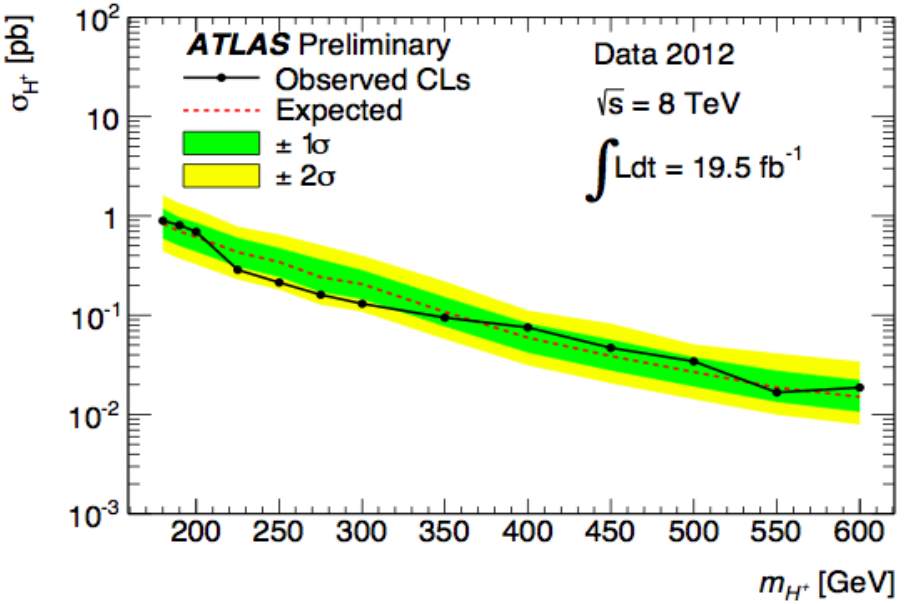




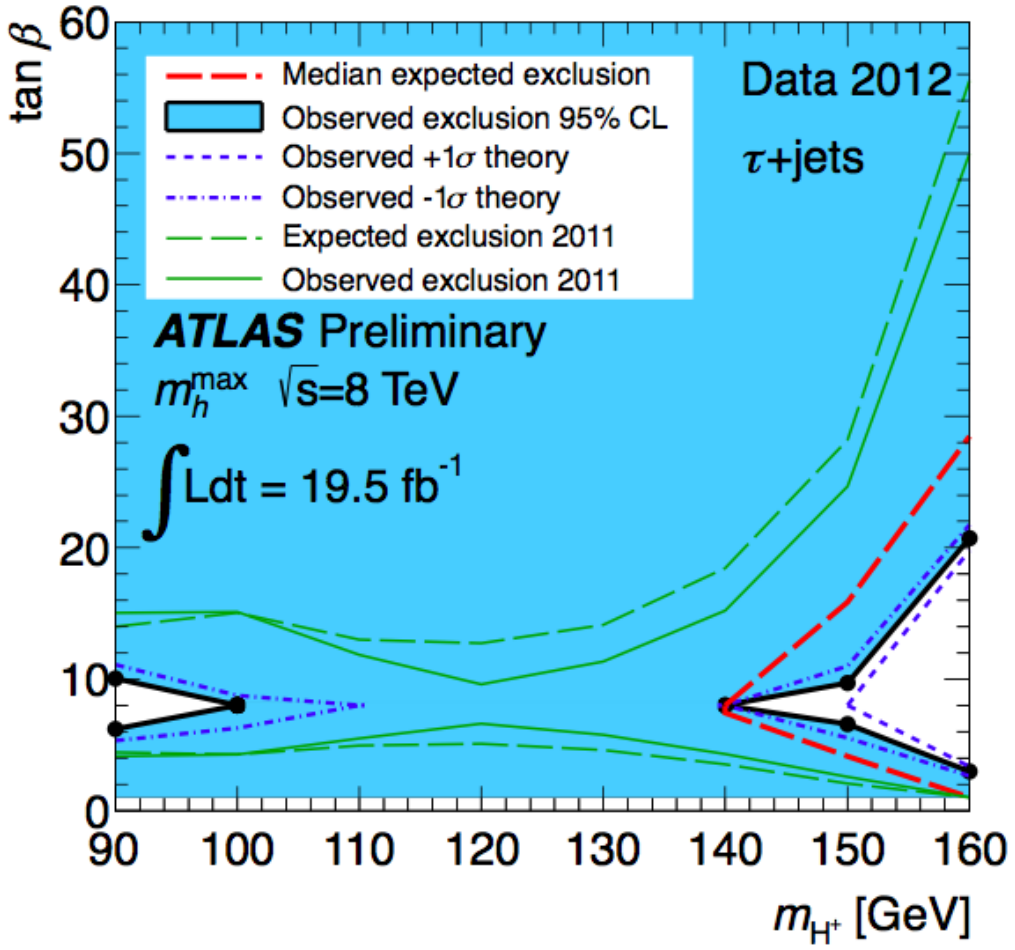
Light (left) and heavy (right) H+ searches

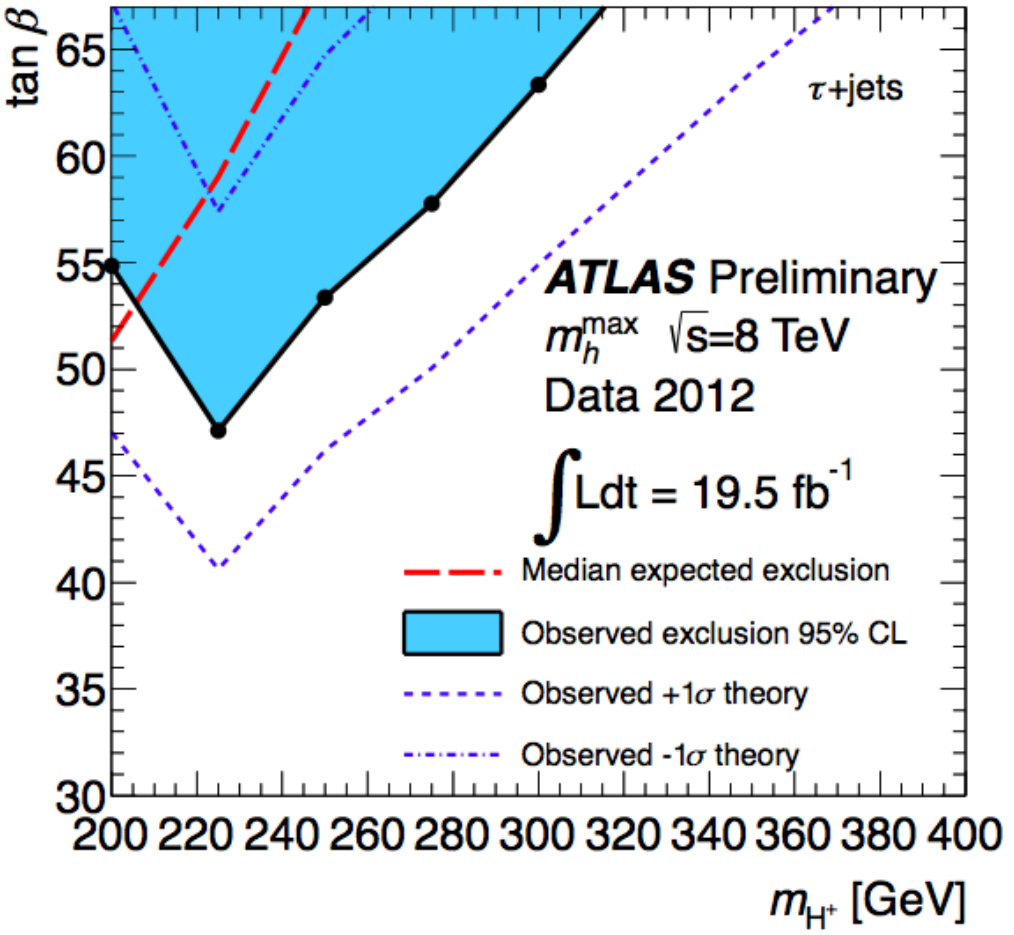
limits set assuming BR ($H^+ \rightarrow \tau\nu$) = 100%





Charged Higgs





Light (left) and heavy (right) H+ searches
limits set assuming MSSM m_h^{max} scenario

Conclusions

- Non-Standard Model properties of 125 GeV Higgs boson, and additional Higgs bosons, expected in well-motivated extensions of the Standard Model
- Extensive searches performed in ATLAS
  - Different channels
  - Different topologies and final states
  - Different experimental methods
- No deviations yet from SM predictions
  - Model-independent limits
  - Interpretations in BSM models
    - 2HDM
    - MSSM
- Continuing analyses of other channels
- Looking forward to higher-energy running