Beyond the Standard Model Higgs Physics using the ATLAS detector

21st International Conference on Supersymmetry and Unification of Fundamental Interactions.

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On behalf of the ATLAS Collaboration

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$\Delta p \cdot \Delta q \geq \frac{1}{2} \hbar$
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ATLAS EXPERIMENT

BSM Higgs search at ATLAS

- Many search ongoing for extended Higgs sector at ATLAS
- Almost all the searches uses a minimal extension of the Higgs sector like a Two Higgs Doublets Model (2HDM)
- This leads to 5 physical Higgses: $H^{\pm}$, H^0, h^0, A (CP-odd)
- Two types considered:
  - Type-I: all quarks couple to just one of the doublets
  - Type-II: up-type-quarks and down-type-quarks couple to different doublets. (MSSM is an example)
- One can easily accommodate the 125 GeV Higgs in those models

Overview of ATLAS BSM Higgs Searches

- **Charged Higgs:**

  $H^+ \rightarrow \tau^+\upsilon$ + jets (updated)

  $H^+ \rightarrow C\bar{S}$

  Doubly charged Higgs

- **Next to Minimal:**

  NMSSM $a_1 \rightarrow \mu\mu$

  NMSSM $h \rightarrow a_1 a_1 \rightarrow 4\gamma$

- **Neutral Higgs:**

  $H^0 \rightarrow \tau^+\tau^-$ and $\mu^+\mu^-$

  2HDM $H^0 \rightarrow W^+W^-$

  Invisible Higgs

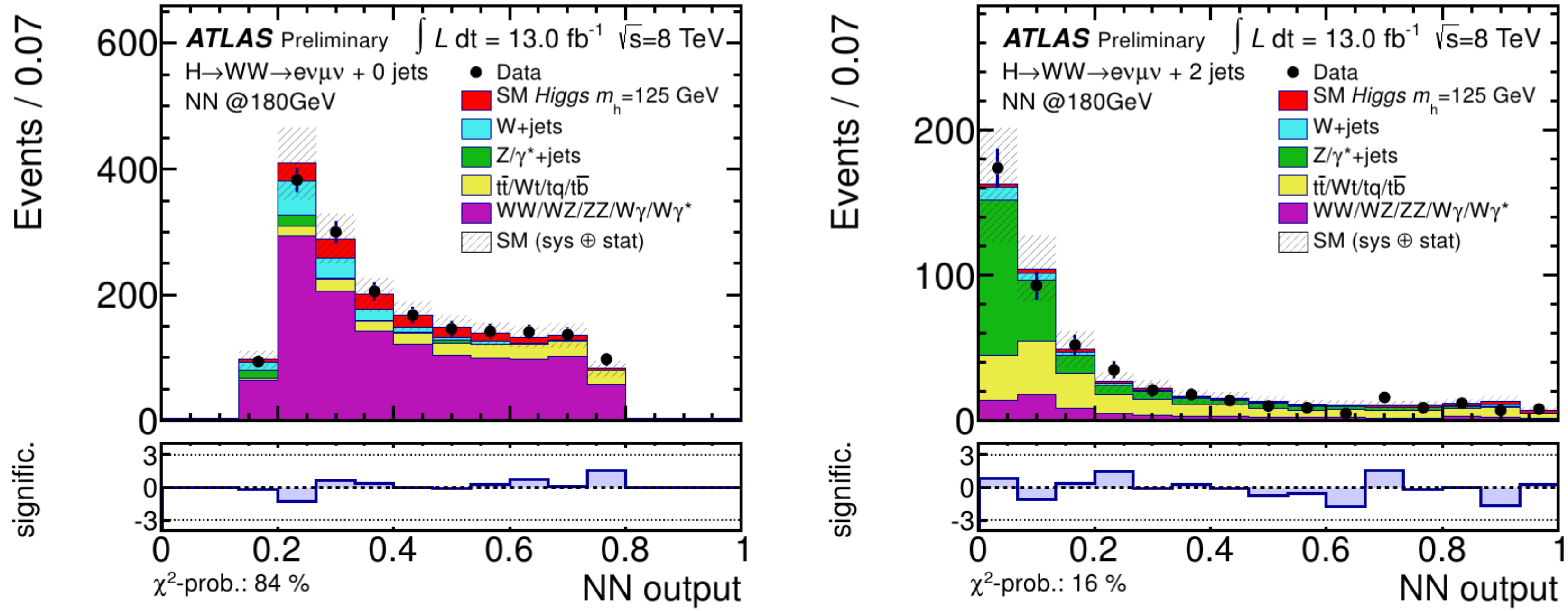
  Fermiophobic $H^0 \rightarrow \gamma\gamma$

  4^{th} fermion generation

For More details:
ATLAS PUBLIC RESULT

Neutral Higgs Searches

2HDM H → WW



- Assumption: "the Higgs" at 125 GeV is the light "h" → search for a heavier neutral H assuming a 2HDM
- Production: gluon fusion and vector boson fusion
- Final state: W decays leptonically, only considered electron-muon, missing energy
- Strategy: split into 0-jet and 2-jet channels
- Discriminant variable: neural network output (trained for different masses)

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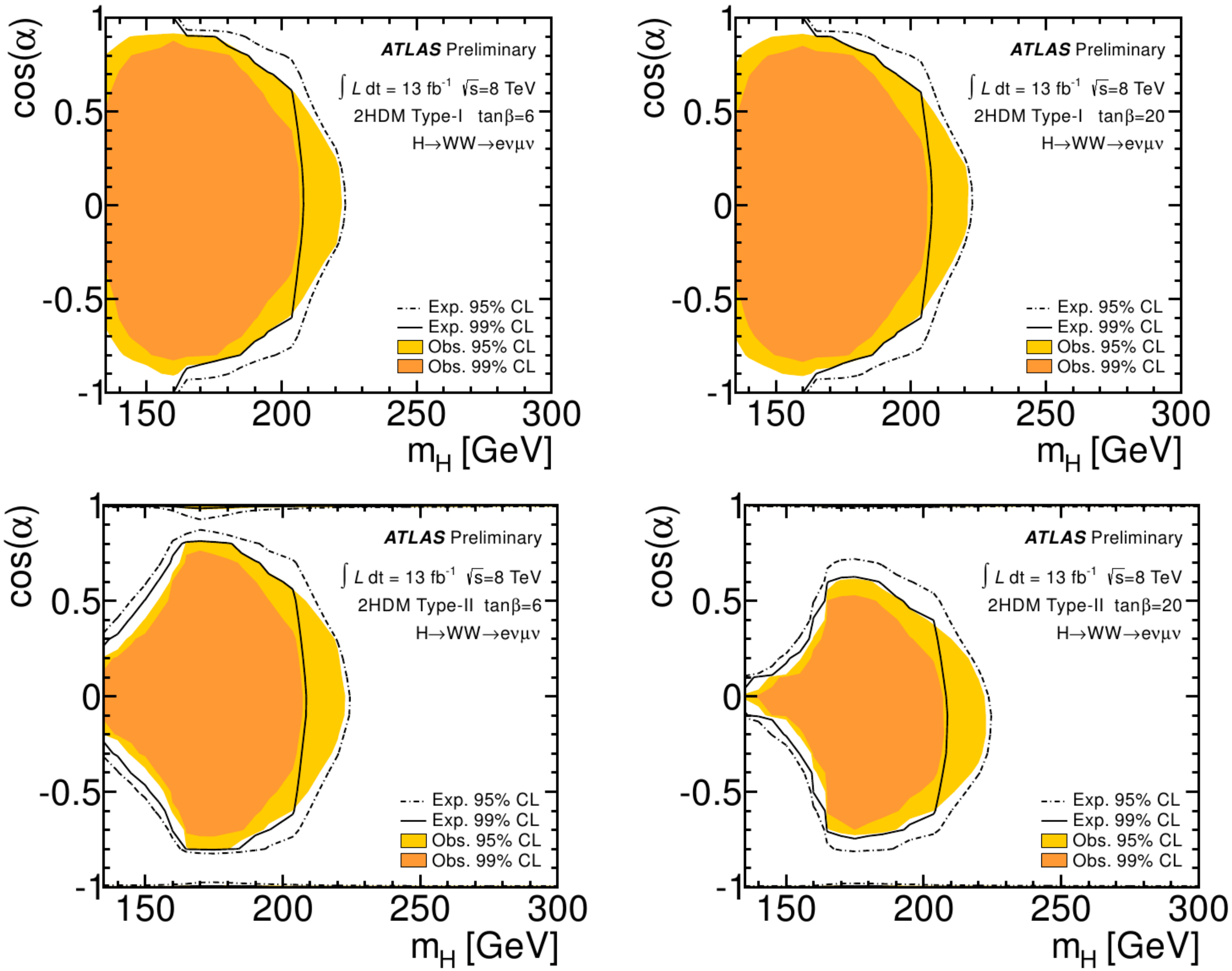
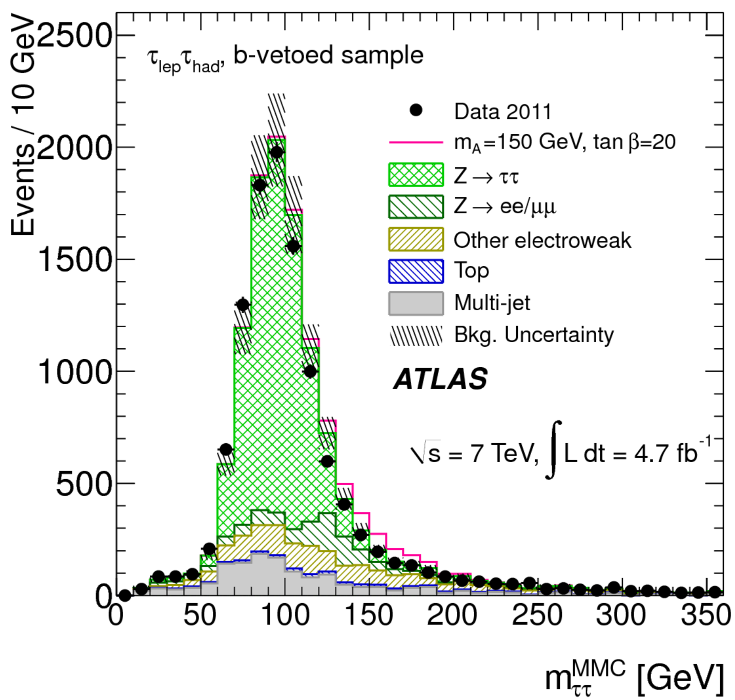
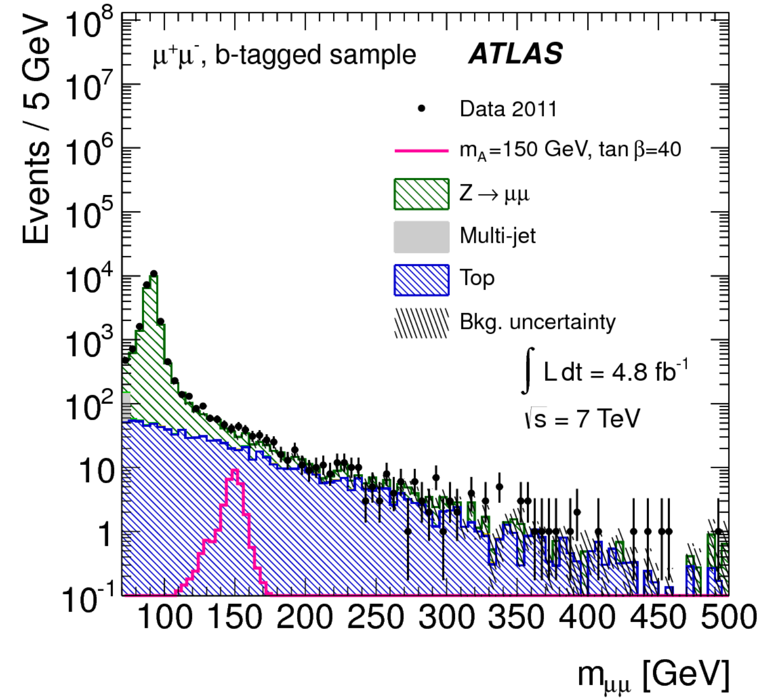
2HDM H → WW: Limits



Exclusion limit set for type-I and II, for tanβ = 1,3,6,20,50

MSSM $H \rightarrow \tau\tau/\mu\mu$





- Search for: Neutral Higgs H/h/A decaying $\tau\tau/\mu\mu$ assuming MSSM
- Production: gluon-fusion and b-associated
- General Strategy: split in b-tag and b-veto categories
- At high tanβ BR to $\tau\tau \sim 10\%$ and to $\mu\mu \sim 0.04\%$, final state considered: $\tau_e\tau_\mu$, $\tau_l\tau_h$, $\tau_h\tau_h$ and $\mu\mu$
- Discriminant variable: di-τ invariant mass (likelihood based method), μμ channel – parametrized background fitted to data (invariant mass scan)

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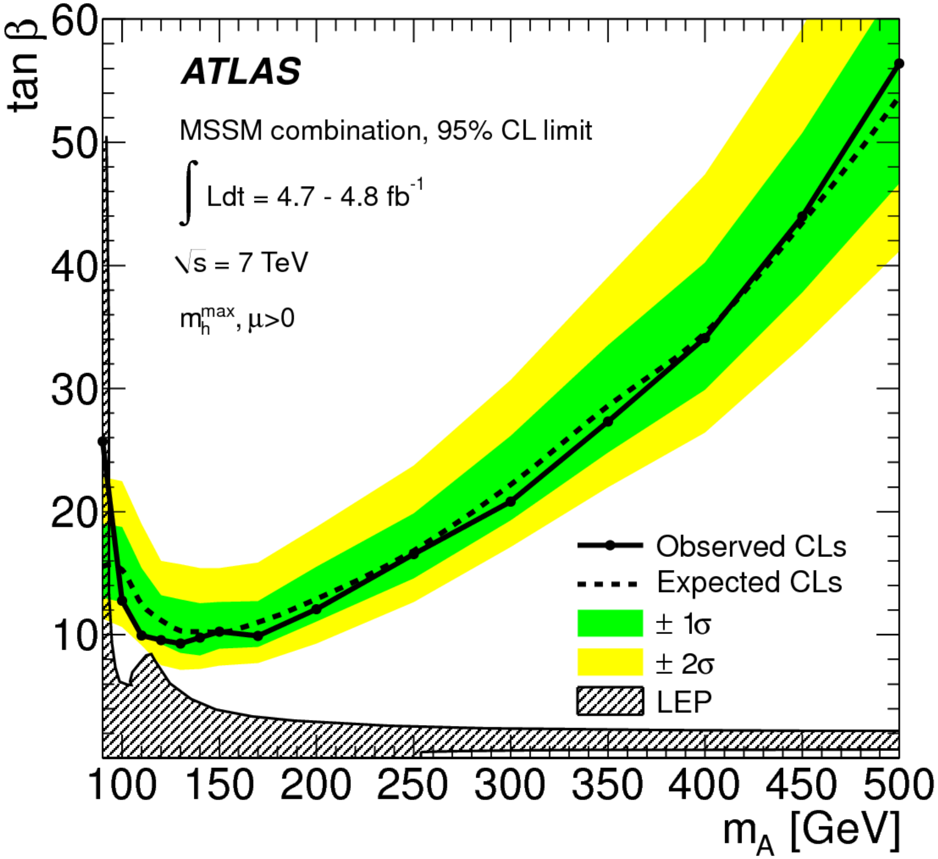
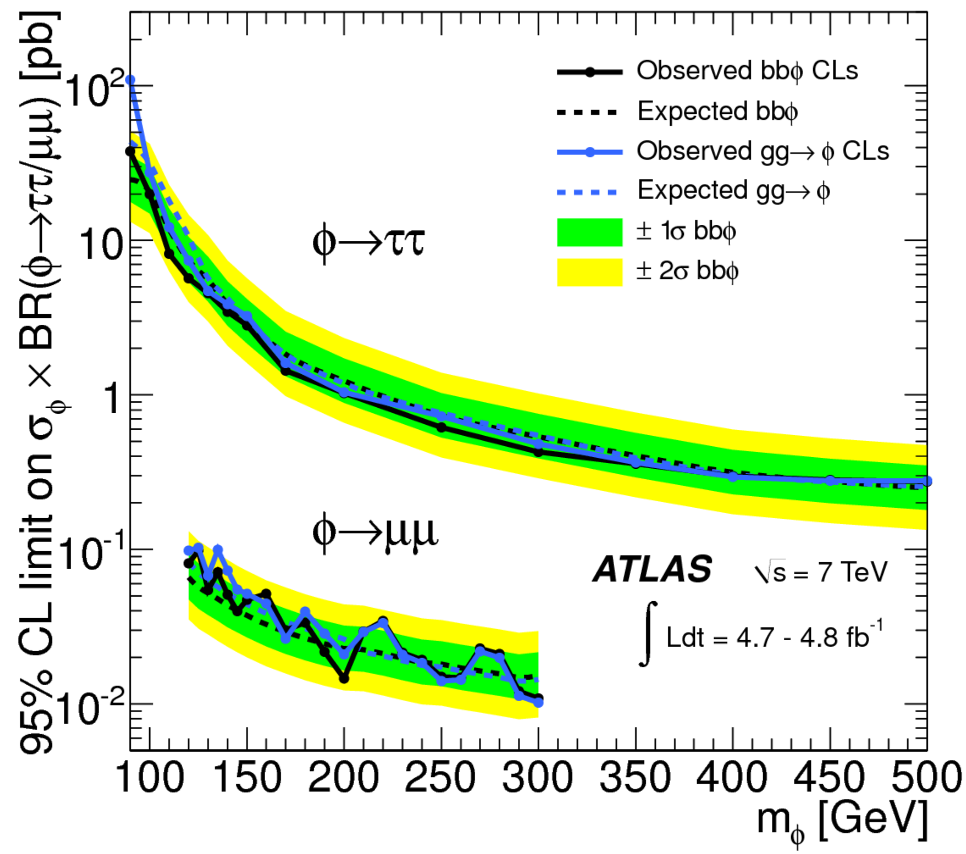
MSSM H → ττ/μμ - Limits:





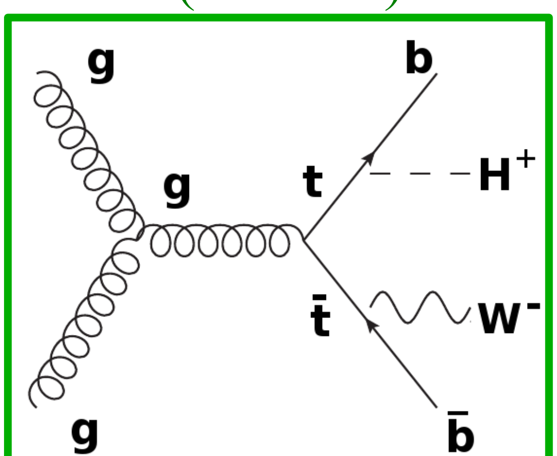
Expected and observed 95% CL limits on tanβ as a function of mA (left), and on the production cross-section times BR for each production mechanism (right). Assuming gluon-fusion and b-associated production.

Charged Higgs Searches

$H^+ \rightarrow \tau^+\upsilon$ + jets: Analysis Overview

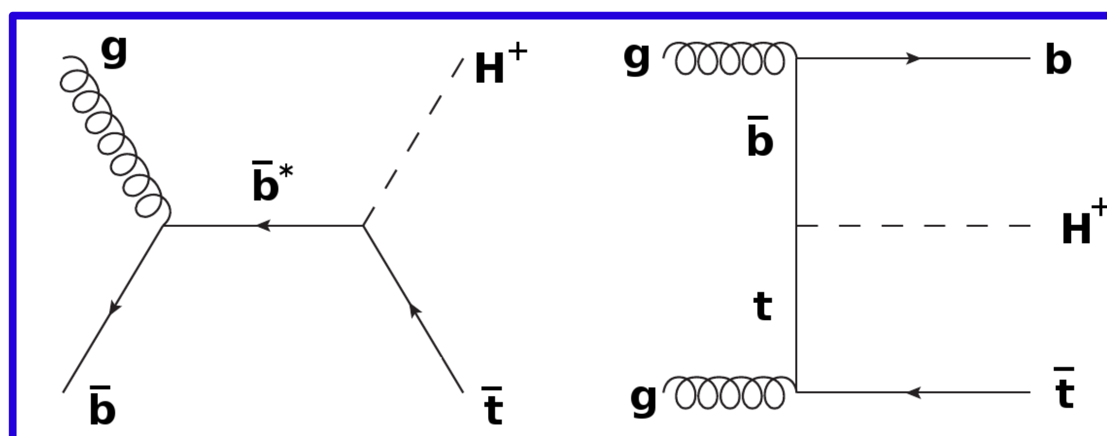
- NOTE: charge conjugated is implied
- First LHC search for Heavy charged Higgs!
- **Analysis Strategy:** Light and Heavy Higgs mass category to take advantage of production channels
- Assuming MSSM: high BR of H^+ to τ^+ over wide range of parameter space
- **Goal** discovery of H^+ or put limits on:

$BR(t \rightarrow H^+ b)$



Top Decay (Light H^+)

σ(top assoc. prod.) $\times BR(H^+ \rightarrow \tau^+\nu)$



Top Associated Production (Heavy H^+)

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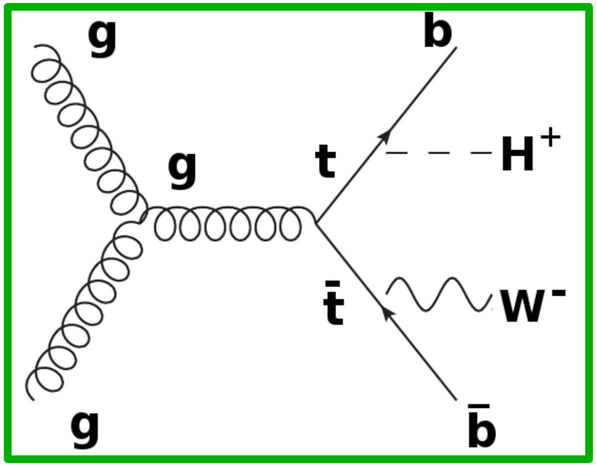
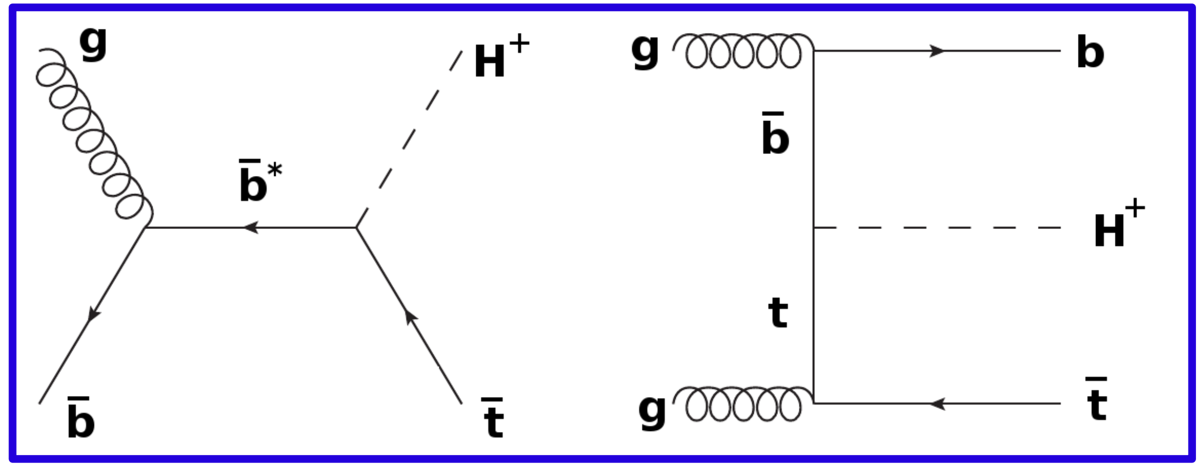
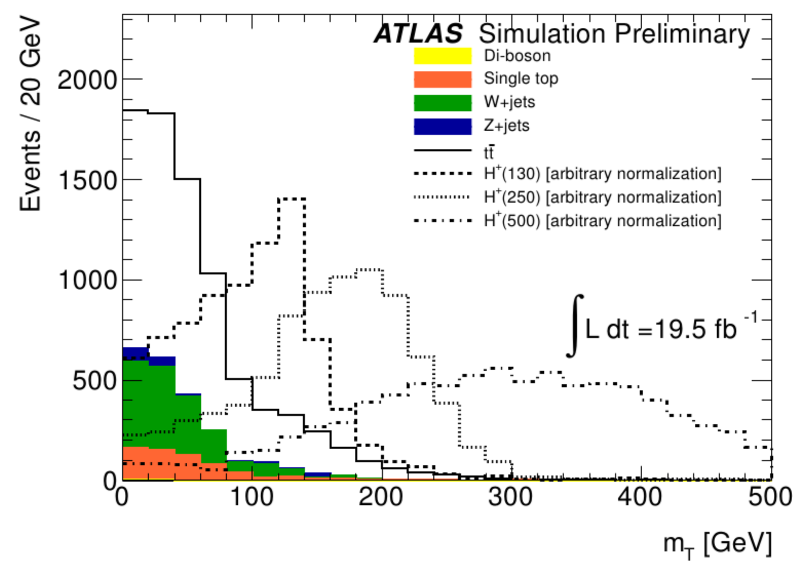
$H^+ \rightarrow \tau^+\upsilon$ + jets: Signal final state





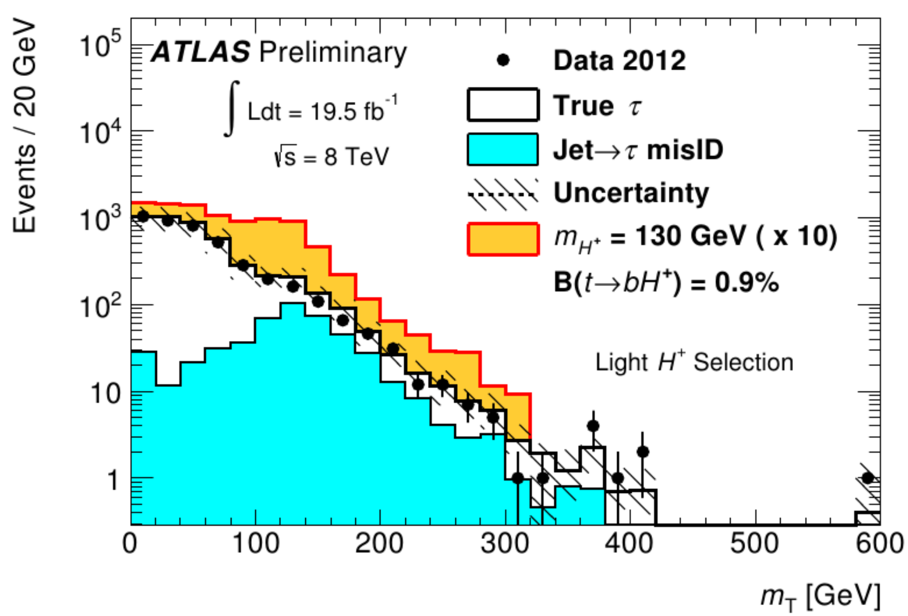
- **Analysis final state selections:**
  - Fully hadronic final state: only W → jets and hadronic τ considered
  - Veto on other leptons
  - 3 or 4 jets of which 1 btagged
  - High Missing Transverse Energy
  - Discriminating variable m_T

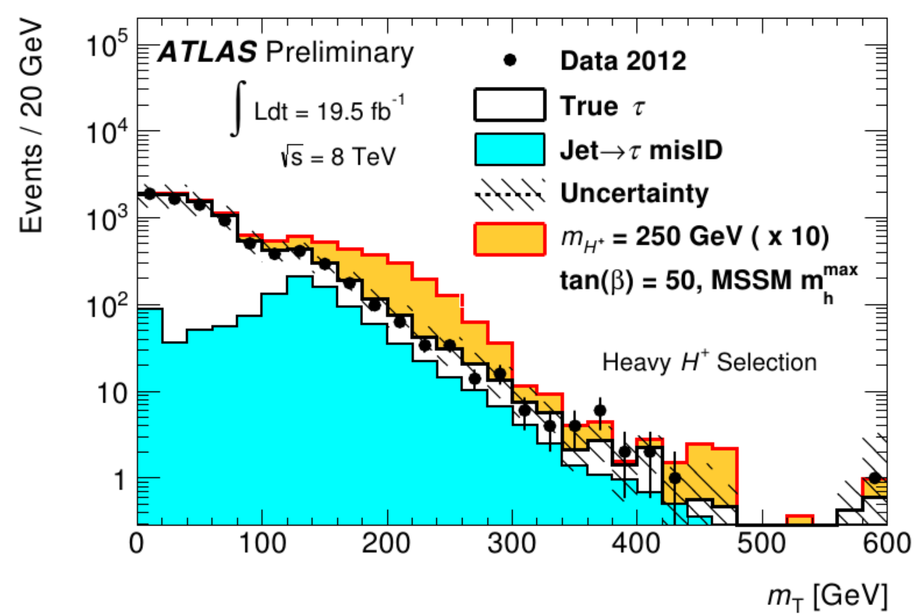


m_T = Transverse invariant mass of tau and Missing Transverse Energy

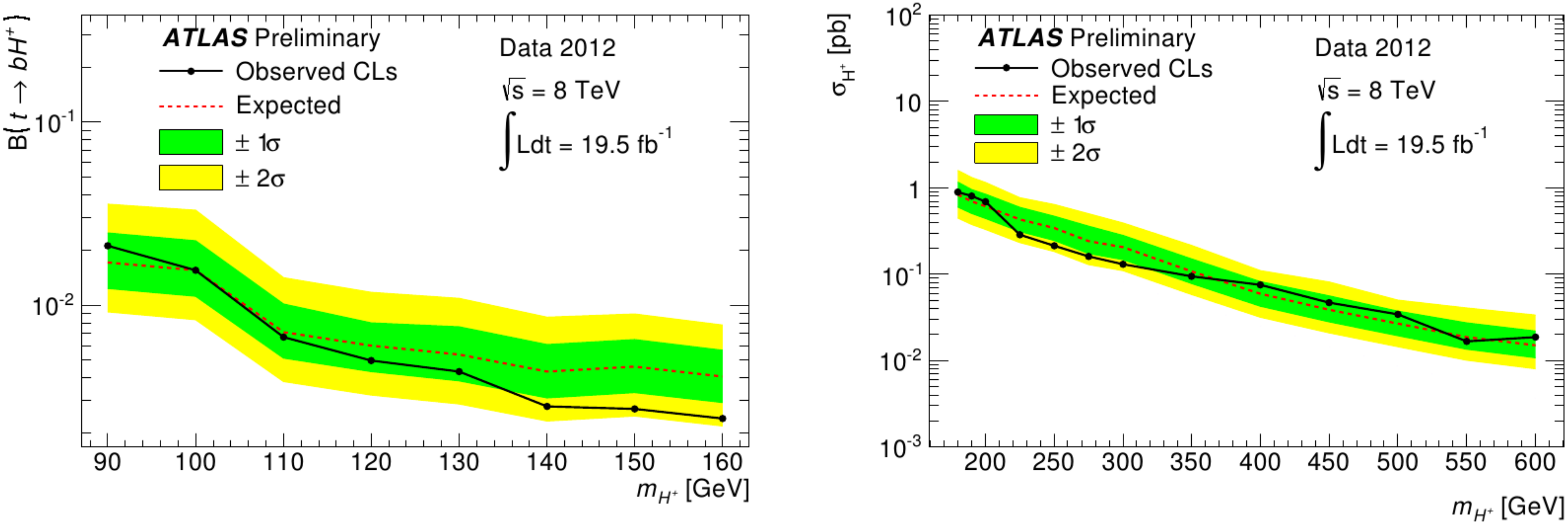
$H^+ \rightarrow \tau^+\upsilon$ + jets: Background Model

- Backgrounds: $t\bar{t}$ and single-top, W and Z + jets, dibosons, QCD multi-jet.
- **Background estimation divided in 2 categories:**
  - Real taus (and an additional lepton-fake taus) contribution → estimated via Simulation
  - Jet-fake taus → estimated via data-driven method: apply to data weights calculated from τ identification and misidentification efficiency





$H^+ \rightarrow \tau^+\upsilon$ + jets: Results

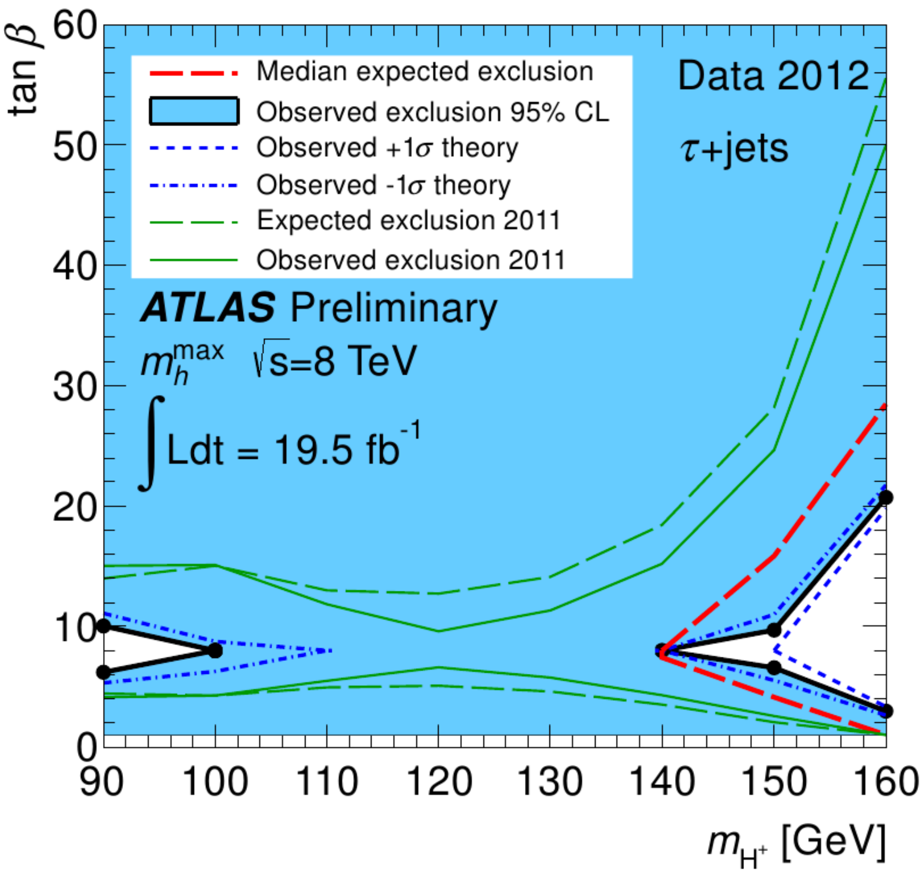


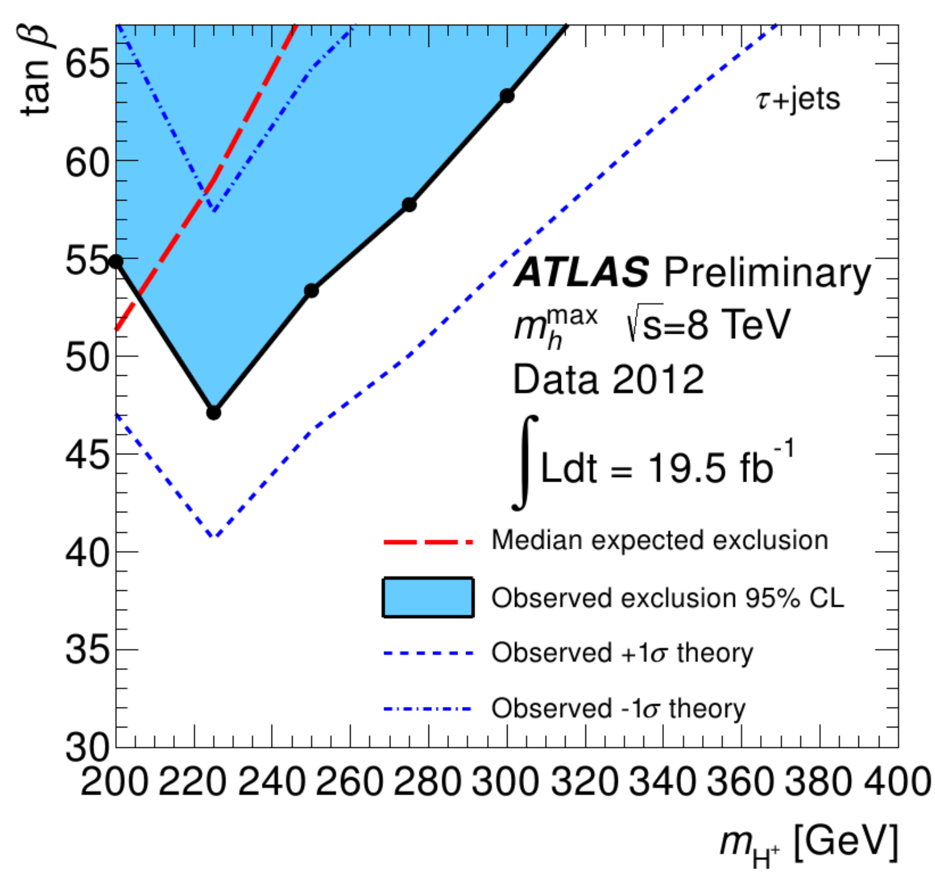
No evidence in data found for the existence of a charged Higgs boson.

Using 2012 full dataset expected and observed 95% CL upper limits are set for:

- Left – Branching ratio of top into charged higgs, assuming BR($H^+ \rightarrow \tau^+\upsilon$) = 1 (light higgs search)
- Right – production cross-section × BR($H^+ \rightarrow \tau^+\upsilon$) (heavy higgs search)

$H^+ \rightarrow \tau^+\upsilon$ + jets: Results





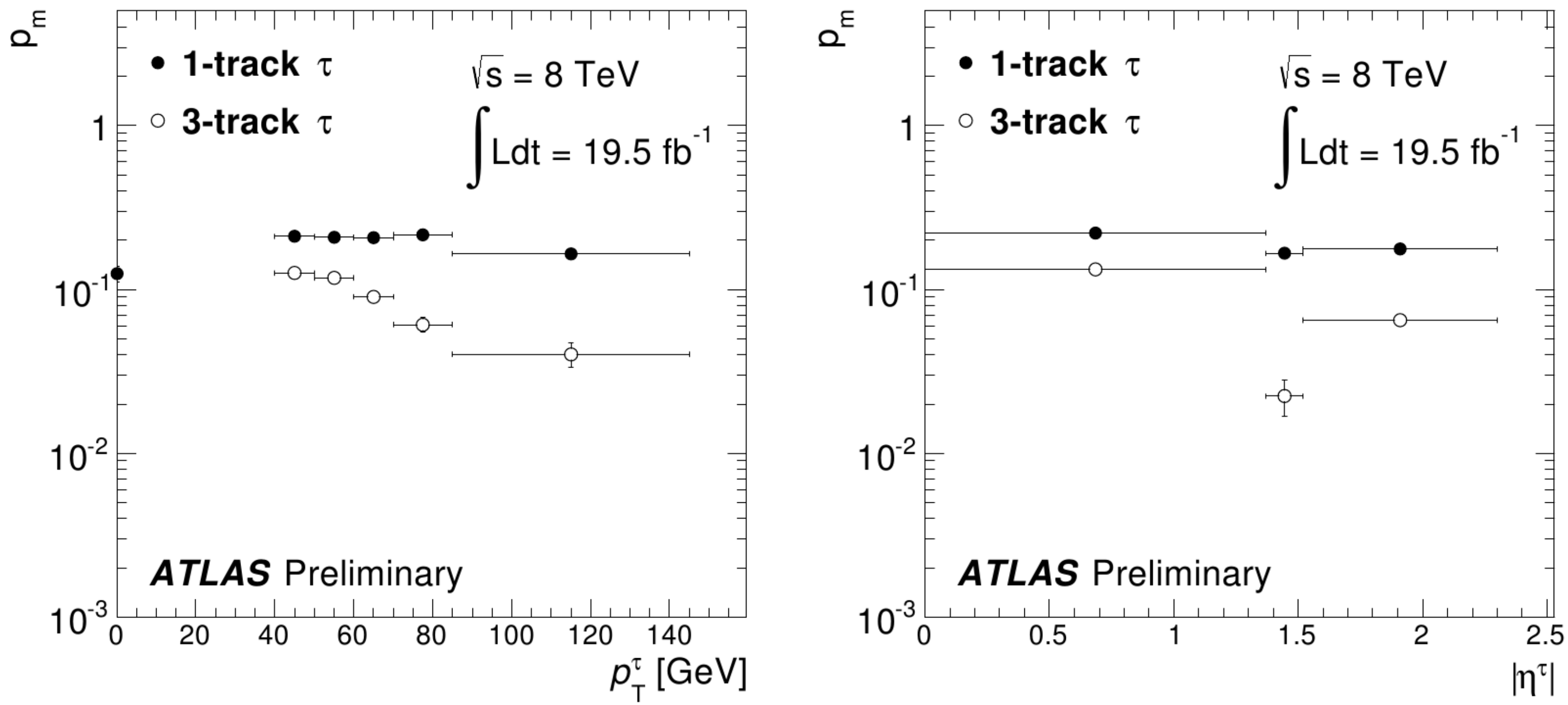
Interpretation in the context of the MSSM m_h^{max} scenario of the limits on BR($t \rightarrow H^+ b$) for light H^+ (left) and production of heavy charged Higgs (right)

Summary

- An update on the search for charged Higgs using the τ+jet channel with 19.5 fb^{-1} has been presented
- No evidence of charged Higgs is found.
- Limits are set at 95% CL on:
  - $BR(t \rightarrow bH^{+})$ in a range of 0.2 - 2.1% for $90 < m_H < 160$ GeV
  - σ(top assoc. prod.) $\times$ $BR(H^{+} \rightarrow \tau^{+}\nu)$ in a range of 0.01 – 0.9 pb for mass $180 < m_H < 600$ GeV
- Many different searches for extended BSM Higgs sector with Atlas, however no evidence found.
- Further analysis still in progress!!!

Additional Material

$H^{\pm}$ data driven jet-fake tau



$$N^L = N_m^L + N_r^L;$$
$$N^T = N_m^T + N_r^T,$$

+

$$p_m = N_m^T / N_m^L;$$
$$p_r = N_r^T / N_r^L$$

$$N_m^T = \frac{p_m}{(p_r - p_m)}(p_r * N^L - N^T)$$

$H^{\pm}$ Systematics table

Variation Detector effects	Shift Up (%)	Shift Down (%)	Shift Up (%)	Shift Down (%)
	light H^+ event selection		heavy H^+ event selection	
$b-$Jet (Mis-)Tag Efficiency Uncertainty	3.1	-3.4	2.9	-3.2
Jet Energy Scale Uncertainties	3.7	-4.8	7.1	-6.8
JVF Uncertainty	2.2	-1.9	2.2	-2.1
$E_{\mathrm{T}}^{\mathrm{miss}}$ Uncertainties	-0.6	-0.2	0.4	0.3
$\tau_{\mathrm{had-vis}}$ e-Veto Uncertainty	0.02	-0.02	0.01	-0.01
$\tau_{\mathrm{had-vis}}$ Energy Scale Uncertainty	3.6	-3.8	3.6	-3.8
$\tau_{\mathrm{had-vis}}$ ID Uncertainty	3.8	-3.8	3.7	-3.7
Pile-up Uncertainties	0.9	-1.5	2.6	-2.1

Variation Data-driven method	Shift (±%)	Shift (±%)
	light H^+ event selection	heavy H^+ event selection
True $\tau_{\mathrm{had-vis}}$ Contamination	3.1	3.3
Jet Composition	10.1	9.8
Statistical Uncertainty on p_m	16.3	13.9
Statistical Uncertainty on p_r	6.7	7.7
$\tau_{\mathrm{had-vis}}$ e-Veto Uncertainty	3.5	3.7
$\tau_{\mathrm{had-vis}}$ ID Uncertainty	9.2	10.9

$H^{\pm}$ observed p_0-values

m_{H^+} (GeV)	90	100	110	120	130	140	150	160
p_0-value	0.29	0.50	0.57	0.69	0.72	0.90	0.94	0.95
m_{H^+} (GeV)	180	190	200	225	250	275	300	350
p_0-value	0.42	0.35	0.37	0.90	0.93	0.94	0.92	0.65
m_{H^+} (GeV)	400	450	500	550	600			
p_0-value	0.27	0.31	0.34	0.62	0.31			

The compatibility with background is measured by p_0-values, probability that a background only hypothesis is as or more compatible with the result than that obtained from the maximum likelihood fit to data with the background+signal model.

2HDM H → WW: NN variables

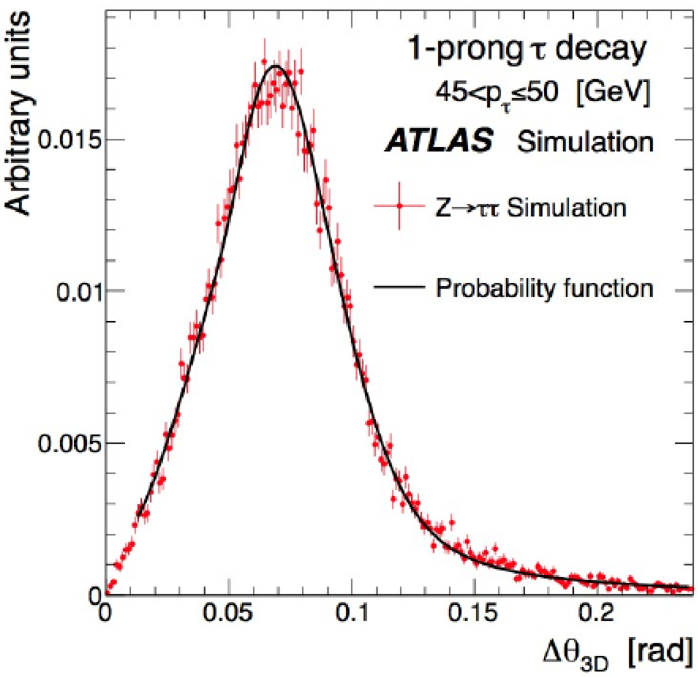
Table 2: Input variables used for the NNs in the 0-jet and 2-jet channels. The definitions of the variables use the terms *leading lepton* and *leading jet*, defined as the lepton/jet with the highest p_{T}.

Variables used in the 0-jet channel and the 2-jet channel	
$\lvert\eta(\ell_1)\rvert$	The absolute value of the pseudorapidity of the leading lepton.
m_{T}	The transverse mass of the lepton-$E_{\mathrm{T}}^{\mathrm{miss}}$system, as defined in Equation 2.
$m(\ell_1\ell_2)$	The invariant mass of the dilepton system.
Variables used in the 0-jet channel only	
$p_{\mathrm{T}}(\ell_1\ell_2)$	The transverse momentum of the dilepton system.
$E_{\mathrm{T,rel}}^{\mathrm{miss}}$	The projection of the calorimeter-based missing transverse momentum.
$\lvert\Delta Y(\ell_1\ell_2)\rvert$	The absolute value of the rapidity differences of the two charged leptons.
Variables used in the 2-jet channel only	
$p_{\mathrm{T}}(\ell_2)$	The transverse momentum of the second-leading lepton.
$p_{\mathrm{T}}(j_1)$	The transverse momentum of the leading jet.
$m(j_1)$	The mass of the leading jet.
$\cos\theta(\ell_1,\ell_2)$	The cosine of the angle between the two charged leptons.
$m(j_1 j_2)$	The invariant mass of the dijet system.
$p_{\mathrm{T}}^{\mathrm{tot}}$	The total transverse momentum, defined as the magnitude of the vector sum of the transverse momenta of the two jets, the two leptons and the missing transverse momentum: $p_{\mathrm{T}}^{\mathrm{tot}} = \lvert\mathbf{p}_{\mathrm{T}}^{\mathrm{tot}}\rvert = \lvert\mathbf{p}_{\mathrm{T}}^{\ell 1} + \mathbf{p}_{\mathrm{T}}^{\ell 2} + \mathbf{p}_{\mathrm{T}}^{j1} + \mathbf{p}_{\mathrm{T}}^{j2} + \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}\rvert$.

MMC in MSSM H → ττ

- From 6 to 8 unknowns in the final state (depending on τ decays)
- Only 4 constraint
- Scan parameter space, calculate di-tau invariant mass and weight it by the tau decay likelihood distribution
- Most probable invariant mass used as estimator

$$\not{E}_{T_x} = p_{\text{mis}_1} \sin\theta_{\text{mis}_1} \cos\phi_{\text{mis}_1} + p_{\text{mis}_2} \sin\theta_{\text{mis}_2} \cos\phi_{\text{mis}_2}$$
$$\not{E}_{T_y} = p_{\text{mis}_1} \sin\theta_{\text{mis}_1} \sin\phi_{\text{mis}_1} + p_{\text{mis}_2} \sin\theta_{\text{mis}_2} \sin\phi_{\text{mis}_2}$$
$$M_{\tau_1}^2 = m_{\text{mis}_1}^2 + m_{\text{vis}_1}^2 + 2\sqrt{p_{\text{vis}_1}^2 + m_{\text{vis}_1}^2}\sqrt{p_{\text{mis}_1}^2 + m_{\text{mis}_1}^2} - 2 p_{\text{vis}_1} p_{\text{mis}_1} \cos\Delta\theta_{vm_1}$$
$$M_{\tau_2}^2 = m_{\text{mis}_2}^2 + m_{\text{vis}_2}^2 + 2\sqrt{p_{\text{vis}_2}^2 + m_{\text{vis}_2}^2}\sqrt{p_{\text{mis}_2}^2 + m_{\text{mis}_2}^2} - 2 p_{\text{vis}_2} p_{\text{mis}_2} \cos\Delta\theta_{vm_2}$$



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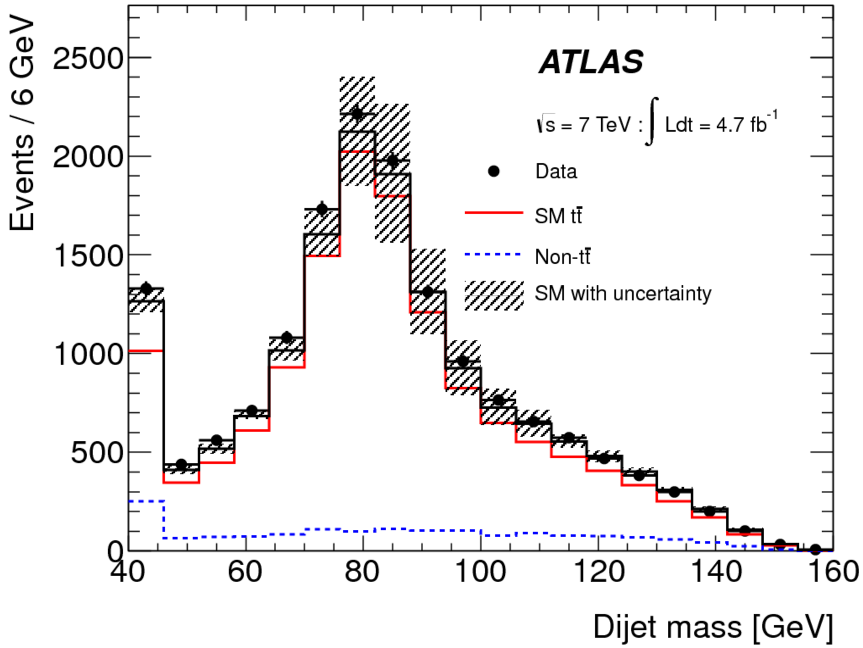
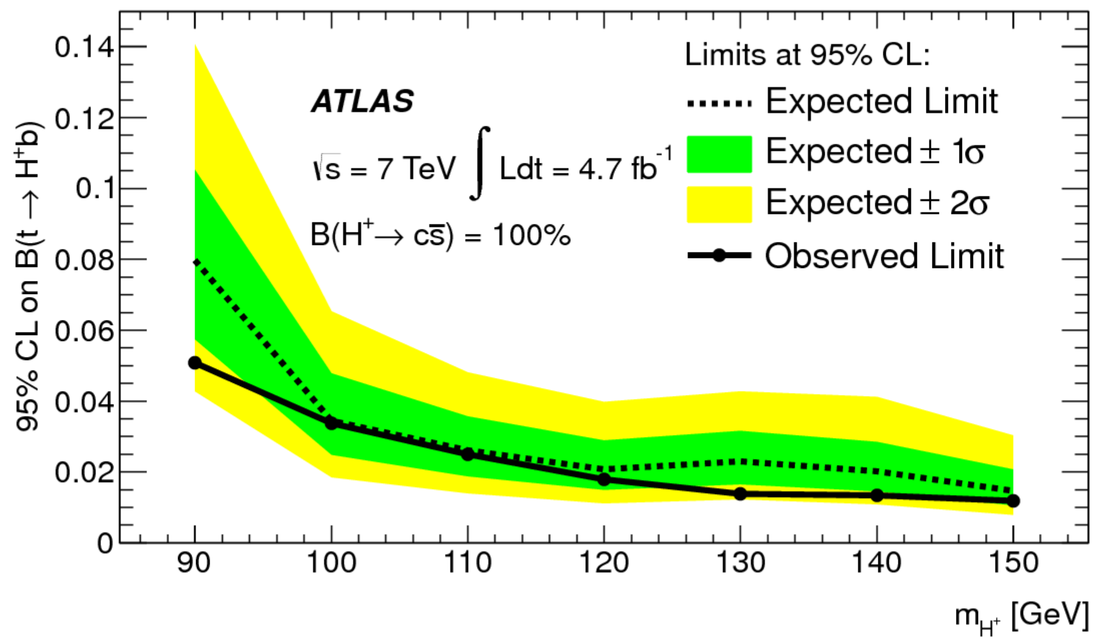
$H^+ \rightarrow c\bar{s}$ in $t\bar{t}$ events





- Search for: Light charged Higgs in top decays (as previously).
- In MSSM for tgβ < 1 BR($H^+ \rightarrow c\bar{s}$) ~ 70% for mass ~ 110 GeV
- Final state: $H^\pm \rightarrow$ 2jets, and leptons from second top.
- Selections: e/μ and ≥ 4 Jets (of which 2 b-tagged) High Missing Energy
- Discriminant variable: di-jet invariant mass. Using Kinematic fitter to fully reconstruct top decay.
- Upper limits on BR($t \rightarrow bH^+$) are set.

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