Search for a high mass Higgs boson in fermionic decay modes using the ATLAS detector

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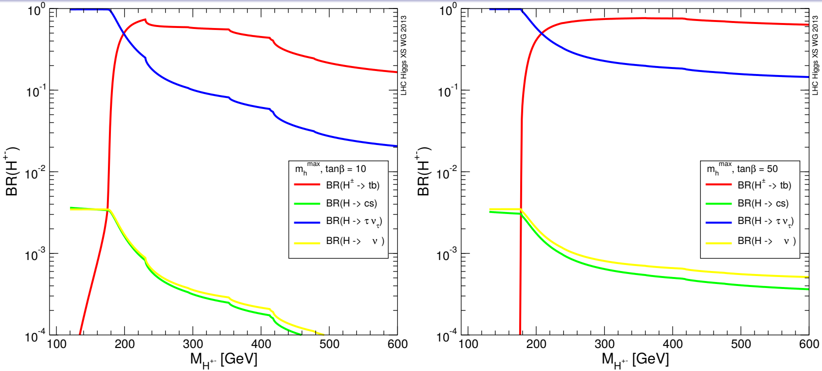
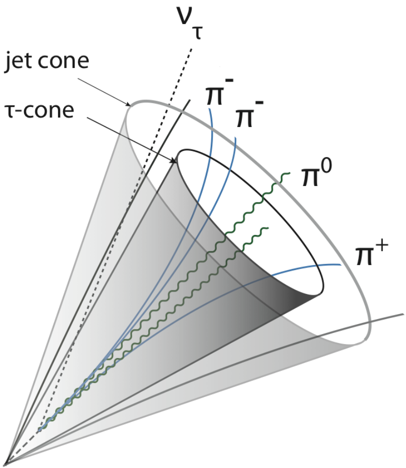
ATLAS EXPERIMENT

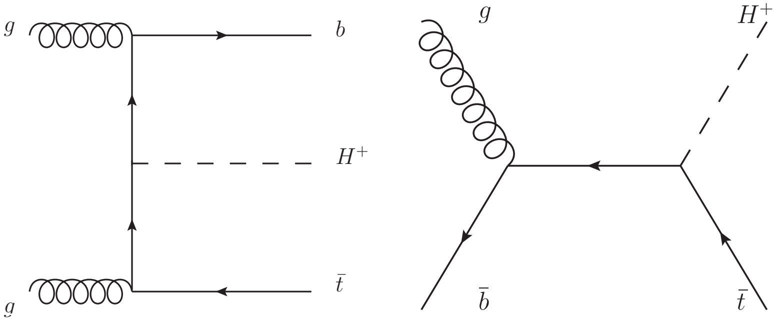


- Extensions of the standard model often include an extended Higgs sector
- Minimal supersymmetry includes two Higgs doublets, with 5 Higgs bosons after electroweak symmetry breaking (h, H, $H^{\pm}$, A)
- The dominant decay modes are fermionic over large regions of parameter space
  - An example for $H^{\pm}$ in an MSSM benchmark scenario is shown above, where $\tan\beta$ is the ratio of the vacuum expectation value of the two Higgs doublets
- This talk will focus on two ATLAS searches ($H^+ \to \tau^+\nu_\tau$ and $H/A \to \tau^+\tau^-$) with results from 2015's dataset (3.2 fb^{-1} at $\sqrt{s} = 13$ TeV)

A brief aside on τ decays

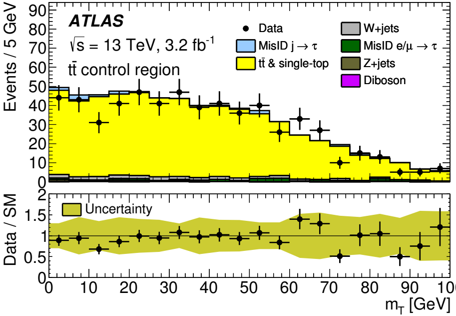
- Recall that τ decay hadronically about 65% of the time
- These form narrow jets, typically with 1 or 3 tracks
- τ_{had} will be used to denote the visible part of hadronic tau decays

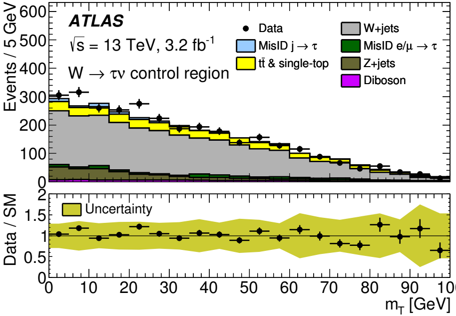




- [Search](#) for singly-charged heavy ($m_{H^+} > m_t$) Higgs bosons produced in association with a top quark, by one of the above (4FS left, 5FS right)
- Decaying as $H^+ \to \tau^+\nu_\tau$ (or the charge-conjugate process)
- Considers the channel where τ and t decay hadronically (τ+jets final state)
- Mass range $200 < m_{H^+} < 2000$ GeV
- Uses 3.2 fb^{-1} pp collision data at $\sqrt{s} = 13$ TeV recorded by ATLAS (2015 dataset)

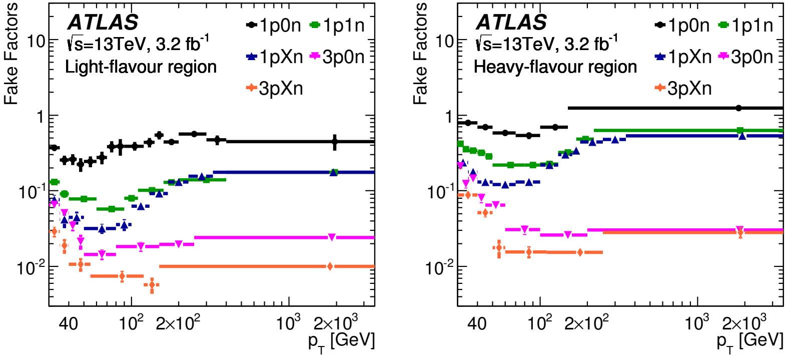
- Backgrounds with true τ_{had} estimated from simulation
  - Dominant backgrounds validated in control regions with $m_T(\tau_{\text{had}}, E_T^{\text{miss}}) \equiv \sqrt{2p_T^{\tau_{\text{had}}} E_T^{\text{miss}}(1 - \cos\Delta\phi_{\tau,\text{miss}})} < 50$ GeV and at least 2 ($t\bar{t}$) or exactly 0 ($W \to \tau\nu$) b-tagged jets



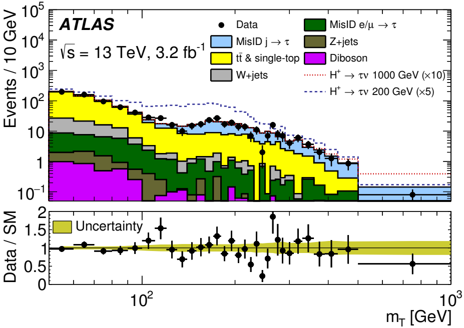


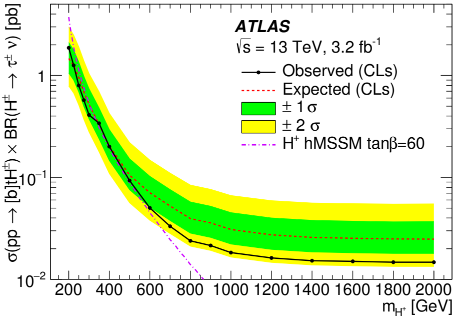
- Backgrounds with $e/\mu \to \tau_{\text{had}}$ are only about 5% of total background, estimated from simulation

- Backgrounds with jet $\to \tau_{\text{had}}$ fakes estimated using data-driven "fake factor" method
    - $FF = \frac{N_\tau}{N_{\text{anti-}\tau}}$ in a fake-enriched control region (0 b, low E_T^{miss}), where anti-τ includes objects failing the nominal τ selection but passing a looser one
    - FF parameterized by τ p_T, decay mode, and b-tagging score (for fakes from light/heavy flavour jets)

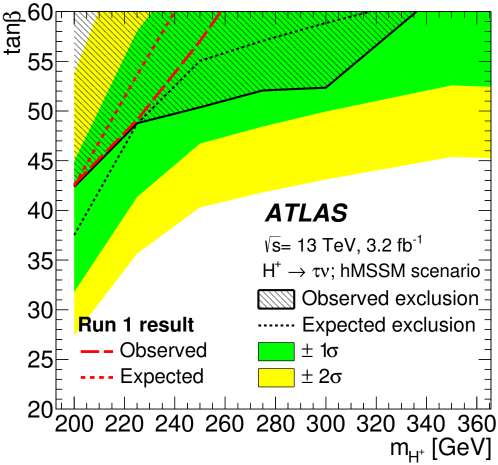


- $N_{\text{fakes}}^{\tau_{\text{had}}} = \sum_i N_{\text{anti-}\tau_{\text{had}}}(i) \times FF(i)$ over each bin i, to get fake contribution in signal region

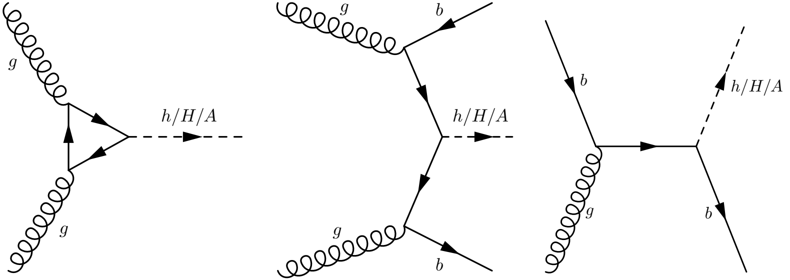




- $m_T(\tau_{\text{had}}, E_T^{\text{miss}}) \equiv \sqrt{2p_T^{\tau_{\text{had}}} E_T^{\text{miss}}(1 - \cos\Delta\phi_{\tau,\text{miss}})}$ discriminant after event selection and fit to background-only hypothesis (left)
  - In good agreement with SM predictions
- Corresponding limits on production cross-section times branching ratio

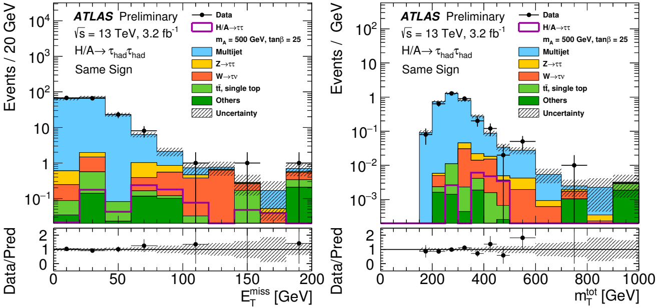


- Expected and observed limits on m_{H^+} and $\tan\beta$ in hMSSM benchmark scenario, an improvement upon the limits set in run 1 of the LHC

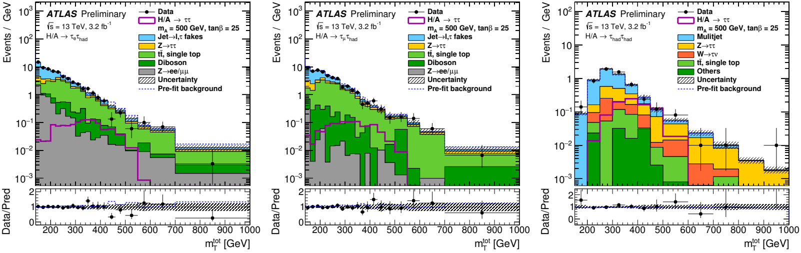


- Search for neutral Higgs bosons produced by gluon fusion (left) or in associated production with one or two b quarks (4FS center, 5FS right), decaying to $\tau^+\tau^-$
- Includes $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channels
  - $\tau_{\text{lep}}\tau_{\text{had}} = 1\ \ell$ (e or μ, $p_T > 20$ GeV), $\geq$1 τ_{had} ($p_T > 30$), $\Delta\phi(\tau, \ell) > 2.4$ and have opposite charge, single-lepton trigger
  - $\tau_{\text{had}}\tau_{\text{had}} = 2\ \tau_{\text{had}}(p_T^{\tau_1} > 135$ and $p_T^{\tau_2} > 55)$, $\Delta\phi(\tau_1, \tau_2) > 2.7$ and have opposite charge, single-tau trigger
- Considers mass range $200 < m_{H,A} < 1200$ GeV
- Uses 3.2 fb^{-1} pp collision data at $\sqrt{s} = 13$ TeV recorded by ATLAS (2015 dataset)

- SM backgrounds without fake τ_{had} or fake ℓ are modeled by MC

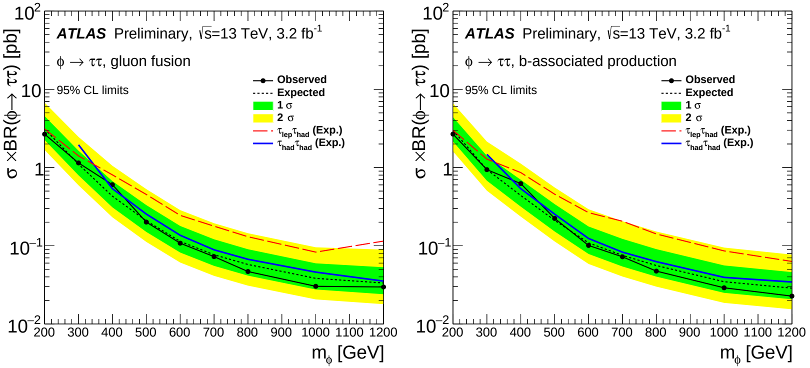


  - Validated in a same-sign control region
- Backgrounds with fake τ_{had} or fake ℓ use a data-driven "fake factor" method binned in τ p_T and number of tracks

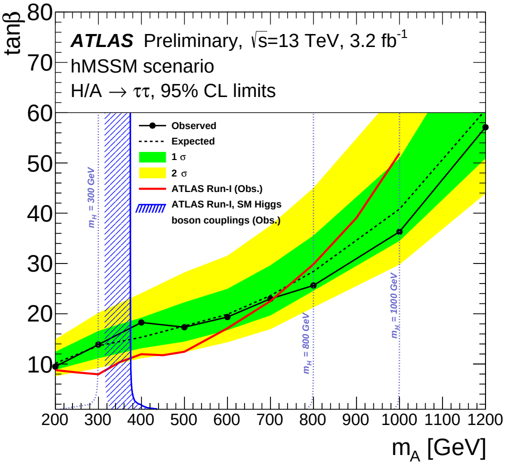


- Likelihood function binned in m_T^{tot} (post-fit shown above) to put limits on signal strength
  - $m_T^{\text{tot}} \equiv \sqrt{m_T^2(E_T^{\text{miss}}, \tau_1) + m_T^2(E_T^{\text{miss}}, \tau_2) + m_T^2(\tau_1, \tau_2)}$ used as a discriminant, where $m_T(a,b) \equiv \sqrt{2 p_T^a p_T^b (1 - \cos \Delta\phi(a,b))}$
- Consistent with SM background-only hypothesis

Results



- Results presented as limits on gluon fusion and *b*-associated production cross section of a scalar particle ϕ times the $\phi \to \tau^+\tau^-$ branching ratio



- Limits on m_A and $\tan\beta$ in hMSSM benchmark scenario, improvement over run 1 limits for $m_A > 700$ GeV

- Results shown for $H^+ \to \tau^+\nu_\tau$ (arxiv) and $H/A \to \tau^+\tau^-$ (CDS) searches
  - No excess observed
  - Improved limits set on production cross-section times branching ratio and model-dependent exclusion regions
- LHC run 2 is just getting started, many analyses in the pipeline, stay tuned for more later this year

$H/A \to \tau^+\tau^-$ Object Definitions

- e
  - Constructed from inner detector track + energy in EM calorimeter
  - $E_T > 15$ GeV and loose identification working point
  - $|\eta| < 2.47$, excluding the calorimeter transition region at $1.37 < |\eta| < 1.52$
  - Gradient isolation requirement
  - Removed if within $\Delta R < 0.2$ of a μ
- μ
  - Constructed from matching tracks in the inner detector and muon spectrometer
  - $p_T > 25$ GeV and loose identification working point
  - $|\eta| < 2.5$
  - Gradient isolation requirement
- Jets
  - Constructed from topoclusters in calorimeter systems
  - Anti-Kt algorithm, $\Delta R = 0.4$
  - Jets with $|\eta| < 2.4$ and $E_T < 50$ GeV must pass Jet Vertex Tagger (pile-up suppression)
  - Not part of event selection, but used in E_T^{miss} calculation
  - Removed if within $\Delta R < 0.2$ of leading $\tau_{\text{had-vis}}$
  - Removed if within $\Delta R < 0.4$ of e or μ
- $\tau_{\text{had-vis}}$
  - Anti-Kt jet, $\Delta R = 0.4$
  - $|\eta| < 2.5$, with $1.37 < |\eta| < 1.52$ excluded
  - $p_T > 25$ GeV
  - 1 or 3 associated tracks, charge ± 1
  - Passes BDT-based tau identification, LLH-based e rejection
  - Removed if within $\Delta R < 0.2$ of e or μ
- E_T^{miss}
  - Negative vectorial sum of p_T of fully calibrated and reconstructed physics objects
  - Includes "soft term" from ID tracks associated w/ primary vertex but not with any physics objects

$H/A \to \tau^+\tau^-$ Event Selection

- $H/A \to \tau_{\text{lep}}\tau_{\text{had}}$
  - Must pass trigger
    - Medium e ID w/ $p_T > 24$ GeV or loose e ID w/ $p_T > 120$ GeV for $e + \tau$ channel
    - Isolated μ w/ $p_T > 20$ GeV or no isolation and $p_T > 50$ GeV for $\mu + \tau$ channel
  - At least one $\tau_{\text{had-vis}}$
    - $p_T > 20$ GeV
    - Medium identification working point
    - If multiple candidates, highest p_T is used, rest treated as jets
  - Exactly 1 ℓ (e or μ)
    - $p_T > 30$ GeV
    - Medium identification working point
    - Matched to trigger object
  - $\tau_{\text{had-vis}}$ and ℓ must have opposite charge
  - $\Delta\phi(\tau, \ell) > 2.4$
  - $m_T(\ell, E_T^{\text{miss}}) < 40$ GeV or > 150 GeV to suppress W background
    - Where $m_T(a, b) \equiv \sqrt{2p_T^a p_T^b(1 - \cos\Delta\phi(a, b))}$
  - In $e + \tau$ channel, veto events in a Z window of $80 < m_{\text{vis}}(\ell, \tau_{\text{vis-had}}) < 110$

$H/A \to \tau^+\tau^-$ Event Selection

- $H/A \to \tau_{\text{had}}\tau_{\text{had}}$
  - Must pass trigger
    - $\tau_{\text{had-vis}}$ with $p_T > 125$ GeV
  - Leading $\tau_{\text{had-vis}}$ (τ_1)
    - $p_T > 135$ GeV
    - Medium identification
    - Trigger matched $(\Delta R < 0.2)$
  - Subleadng $\tau_{\text{had-vis}}(\tau_2)$
    - $p_T > 55$GeV
    - Loose identification
  - $\Delta\phi(\tau_1, \tau_2) > 2.7$ and the τ candidates have opposite charge
  - Exactly 0 ℓ (e or μ), for orthogonality with $\tau_{\text{lep}}\tau_{\text{had}}$ channel
  - $m_T^{\text{tot}} \equiv \sqrt{m_T^2(E_T^{\text{miss}}, \tau_1) + m_T^2(E_T^{\text{miss}}, \tau_2) + m_T^2(\tau_1, \tau_2)}$ used as a discriminant

$H^+ \to \tau^+\nu_\tau$ Object Definitions

- e
  - Constructed from inner detector track + energy in EM calorimeter
  - $E_T > 20$ GeV
  - $|\eta| < 2.47$, excluding the calorimeter transition region at $1.37 < |\eta| < 1.52$
  - Loose electron identification working point
  - Isolation requirement
- μ
  - Constructed from matching tracks in the inner detector and muon spectrometer
  - $p_T > 20$ GeV
  - $|\eta| < 2.5$
  - Loose muon identification working point
  - Isolation requirement
- Jets
  - Constructed from topoclusters in calorimeter systems
  - Anti-Kt algorithm, $\Delta R = 0.4$
  - Jets with $|\eta| < 2.4$ and $E_T < 50$ GeV must pass Jet Vertex Tagger (pile-up suppression)
  - b-quark initiated jets tagged at 70% efficiency (in $t\bar{t}$) working point
  - Removed if within $\Delta R < 0.2$ of leading $\tau_{\text{had-vis}}$
  - Removed if within $\Delta R < 0.4$ of e
- $\tau_{\text{had-vis}}$
  - Anti-Kt jet, $\Delta R = 0.4$
  - $|\eta| < 2.3$
  - $p_T > 40$ GeV
  - 1 or 3 associated tracks, charge ± 1
  - Passes BDT-based tau identification
  - Removed if within $\Delta R < 0.4$ of e, $\Delta R < 0.2$ of μ
- E_T^{miss}
  - Negative vectorial sum of p_T of fully calibrated and reconstructed physics objects
  - Includes “soft term” from ID tracks associated w/ primary vertex but not with any physics objects

- Trigger
  - $E_T^{\text{miss}} > 70$ GeV
- 1 or more $\tau_{\text{had-vis}}$ with $p_T > 40$, highest must pass requirements mentioned before
- 3 or more jets with $p_T > 25$ GeV, at least 1 of which is *b*-tagged
- 0 e or μ with $p_T > 20$ GeV
- $E_T^{\text{miss}} > 150$ GeV, to be above trigger turn-on curve (measured in data)
- $m_T(\tau_{\text{had-vis}}, E_T^{\text{miss}}) \equiv \sqrt{2p_T^{\tau_{\text{had-vis}}} E_T^{\text{miss}}(1 - \cos\Delta\phi_{\tau,\text{miss}})} > 50$ GeV