ATLAS Searches for Higgs Bosons Beyond the Standard Model

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on behalf of the ATLAS Collaboration

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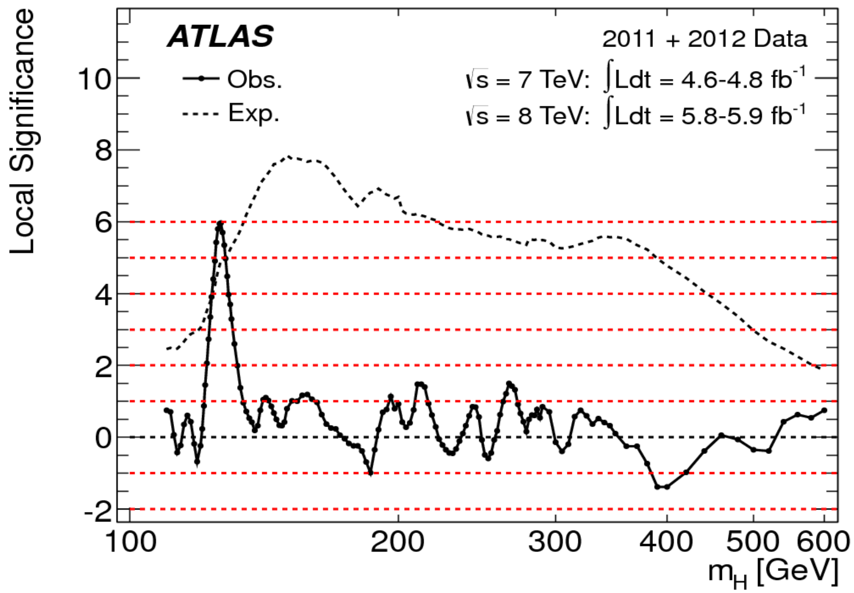
The Higgs landscape, post-discovery



Fireworks in Pittsburgh, July 4 2012
Celebrating announcement of Higgs discovery

- Discovery of a new boson at 125 GeV ushers in a new era in particle physics.
- Coupling and property measurements are critical for establishing its identity and role in EWSB.
- Searches for extended Higgs sectors still relevant! Complementary approach for discovering or constraining new physics.

No Higgs Left Behind

The ATLAS BSM Higgs Suite:

Channel	Lumi (fb^{-1})
2HDM $H \to WW$	13.0
Neutral MSSM $h/A/H \to \mu\mu$	4.8
Neutral MSSM $h/A/H \to \tau\tau$	4.7
Charged $H^+ \to \tau\nu$	4.6
Charged $H^+ \to c\bar{s}$	4.7
Doubly-charged $H^{++} \to ee/\mu\mu$	4.7
NMSSM $a \to \mu\mu$	0.039
NMSSM $H \to aa \to 4\gamma$	4.9

this talk

ATLAS also has results on rare and BSM decays of the Higgs, covered in talks by Renat Ishmukhametov and Andrea Coccaro.

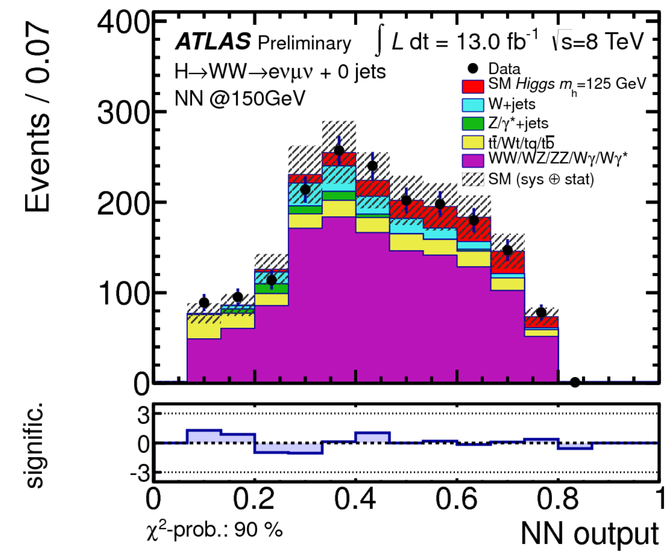
The 2HDM: Introduction

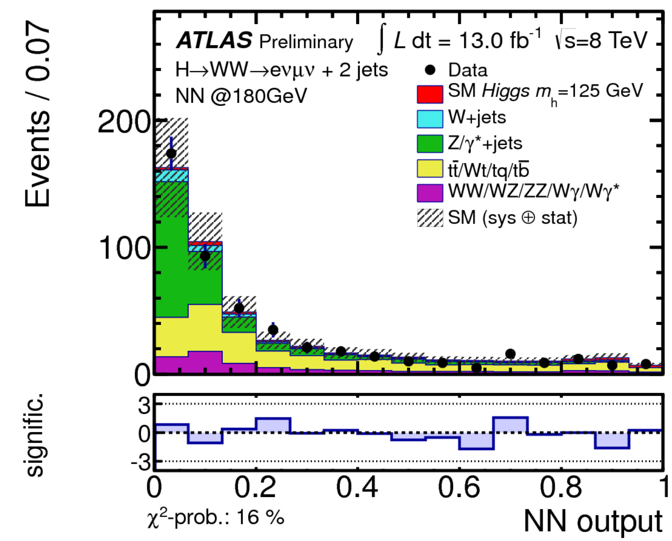
- 2 Higgs Doublets, $H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}$ & $H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$, yield 5 physical Higgs states: H^+, H^- (charged), A (CP-odd), H, h (CP-even).
  - Strategy: assume h is boson at 125 GeV.
- Determined by 4 masses and 2 mixing angles: α and β.
- Two types considered:
  - Type I: All fermions couple to H_2
  - Type II: Up-type fermions couple to H_2, down type to H_1
- We consider the decay $H \rightarrow$ WW for $m_H > 135$ GeV
  - First 2HDM-specific search at the LHC!

ATLAS-CONF-2013-027

2HDM H → WW: Analysis

- Consider the decay $H \to WW \to e\nu\mu\nu$
  - Selection similar to SM $H \to WW$: p_T(lep) > 25/15 GeV; $m(l_1 l_2)$ > 10 GeV; MET_{rel} > 25 GeV.
- Events split into 0-jet and 2-jet categories to target ggH and VBF.
- Background discrimination achieved using Neural Networks, trained for each category and 3 mass points.
- W + jets and top backgrounds estimated using data-driven techniques.

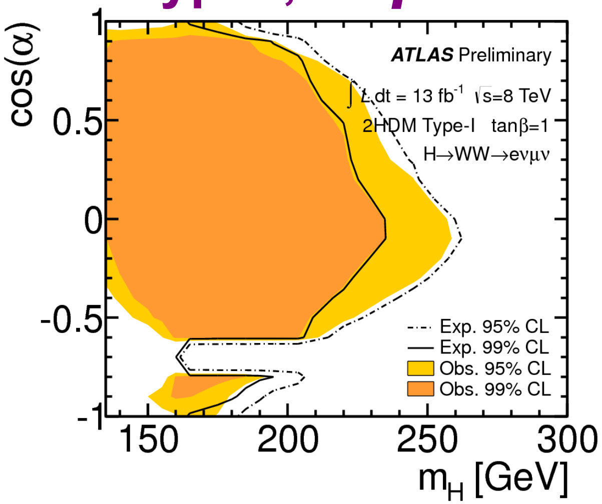




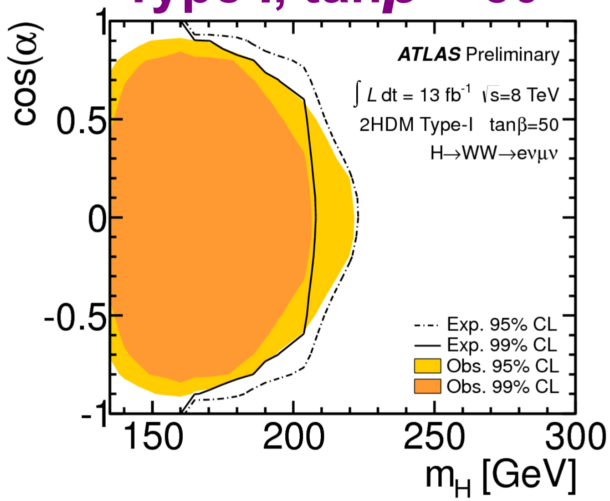
2HDM H → WW: Results

- No evidence of a heavy Higgs is observed.
- Exclusion limits are set in the m_H – cos(α) plane, for Type-I and Type-II 2HDM separately, and for five tan(β) points from 1 to 50.
- Significant regions of the parameter space excluded!

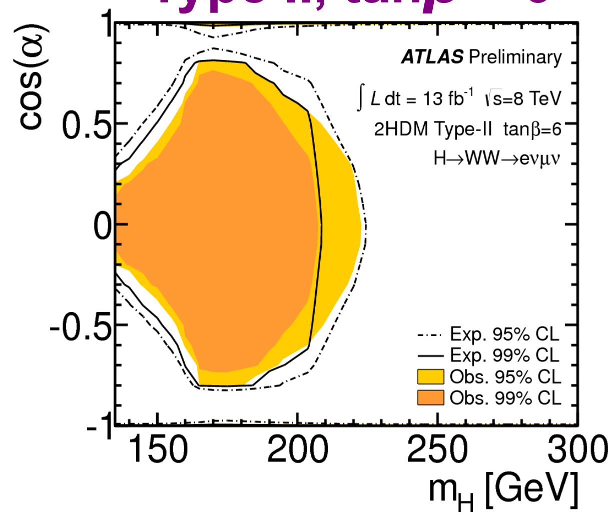
Type I, tan*β* = 1



Type I, tan*β* = 50

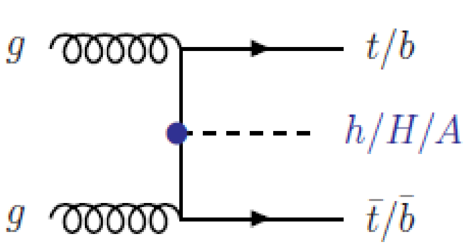


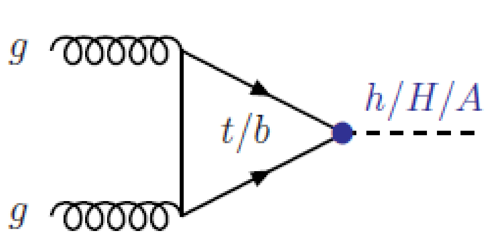
Type II, tan*β* = 6

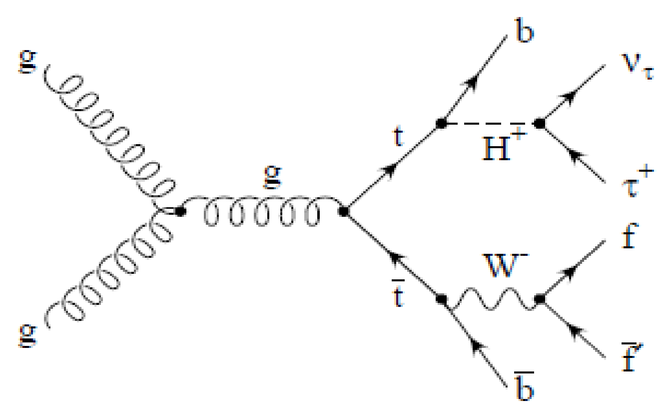


The MSSM Higgs sector

- The MSSM is a Type-II 2HDM, with additional constraints.
  - Described at tree-level by two parameters: m_A & $\tan\beta$.
  - Consistent with a SM-like Higgs at 125 GeV.[1]
- Couplings to down-type fermions enhanced for large $\tan\beta$.
- Neutral Higgs searches focus on the $\tau\tau$ and $\mu\mu$ decay modes, with or without an associated b-jet.
- Charged Higgs searches consider production via top-quark decay, in the $\tau\nu$ and $c\bar{s}$ decay modes.





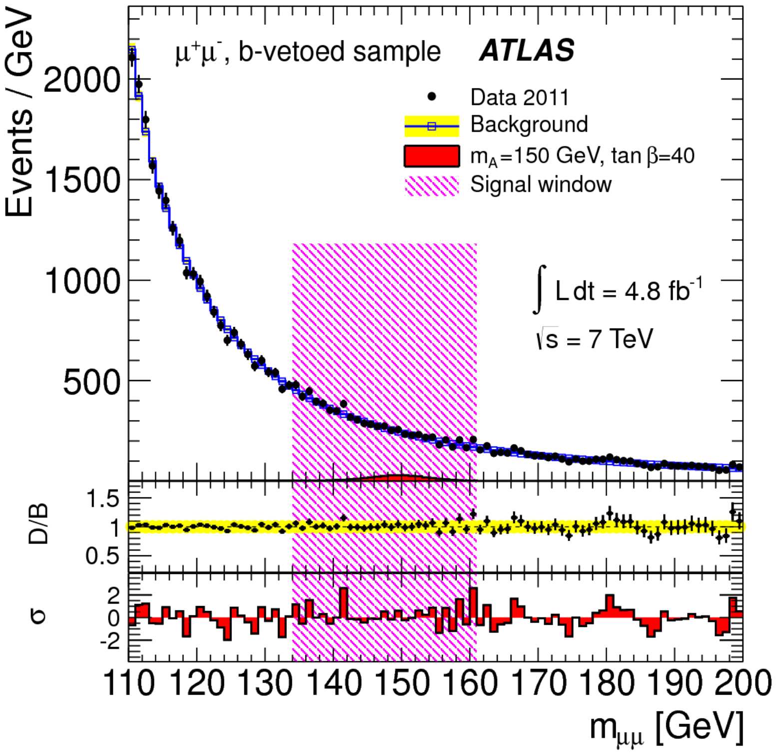


[1] See e.g. http://arxiv.org/abs/1207.1096

arXiv:1211.6956

MSSM Higgs→μμ: Analysis

- Events selected with 2 muons, low missing energy.
- Sample split into categories with and without a b-tagged jet.
- Analysis performed by defining a window for each signal hypothesis, fitting background in the sidebands.



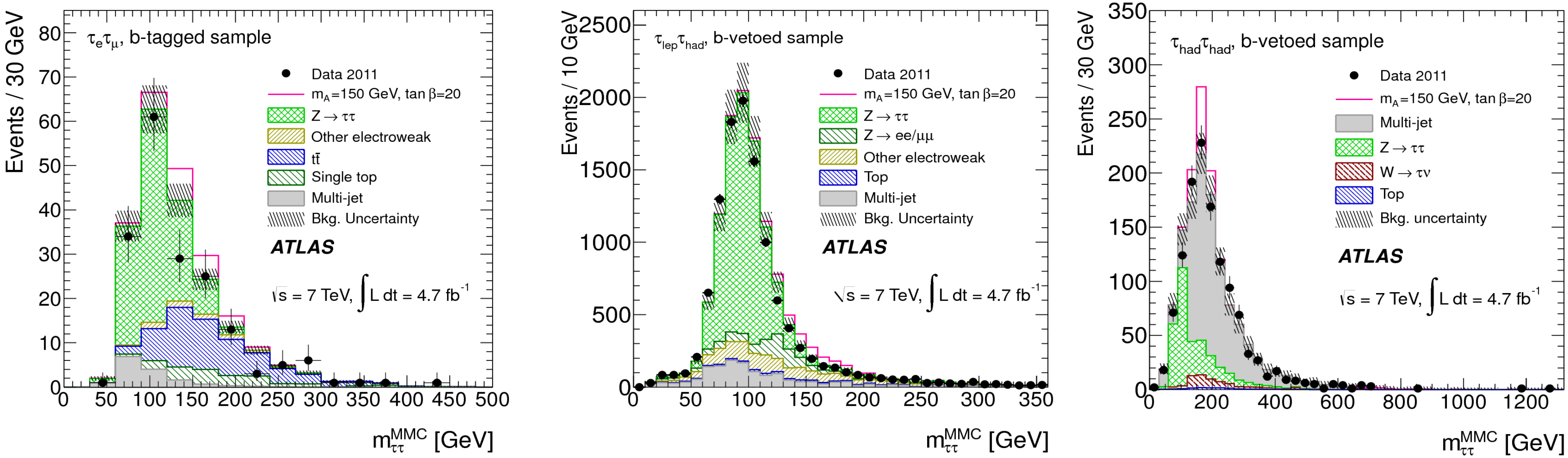
$$f_B(x, N, A, B, M_Z, \Gamma_Z, \sigma) = N \cdot [f_Z(x, A, B, M_Z, \Gamma_Z) \otimes f_{Gauss}(x, \sigma)]$$

$$f_Z(x, A, B, M_Z, \Gamma_Z) = A\frac{1}{x^2} + B\frac{x^2 - M_Z^2}{\left(x^2 - M_Z^2\right)^2 + M_Z^2\Gamma_Z^2} + \frac{x^2}{\left(x^2 - M_Z^2\right)^2 + M_Z^2\Gamma_Z^2}$$

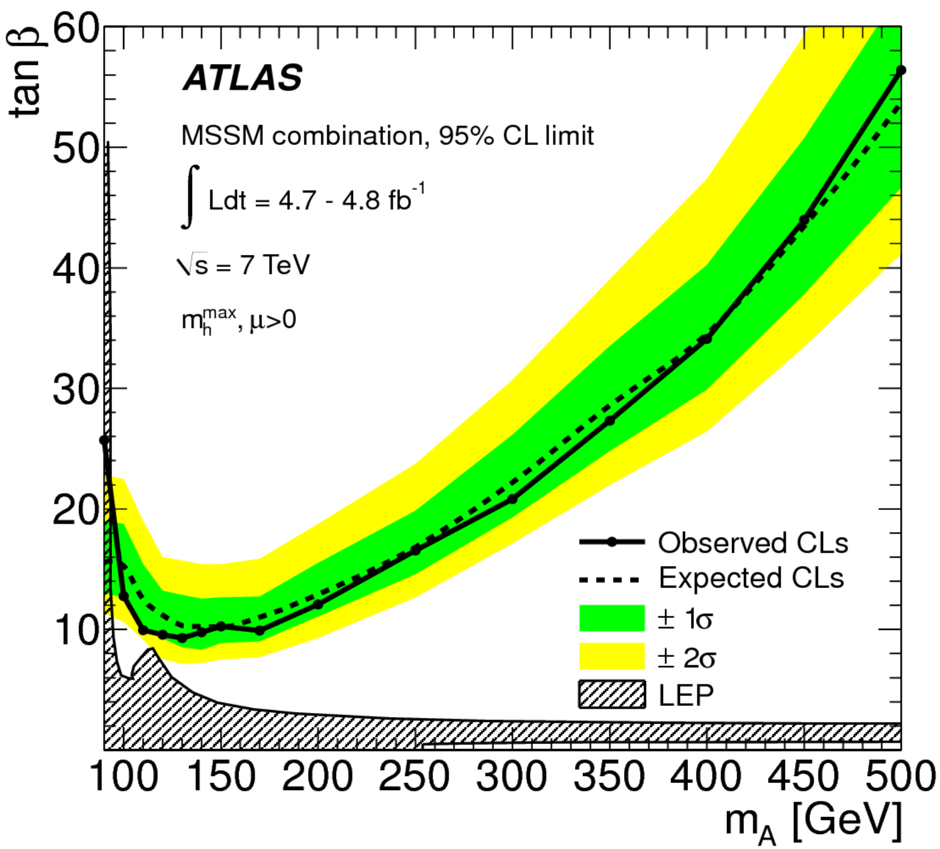
arXiv:1211.6956

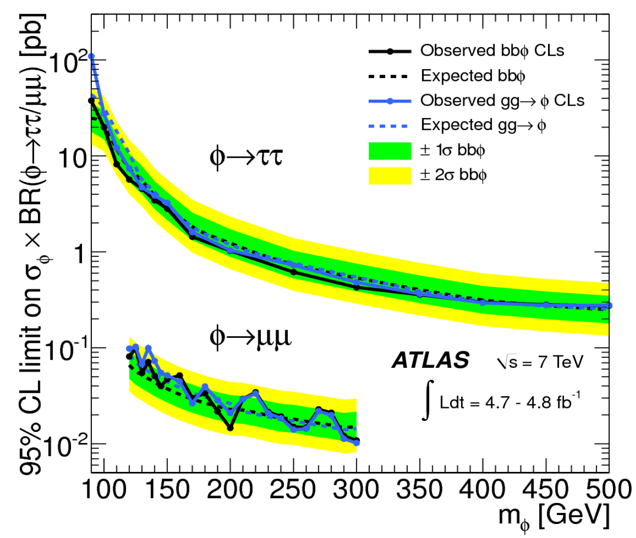
MSSM Higgs→ττ: Analysis

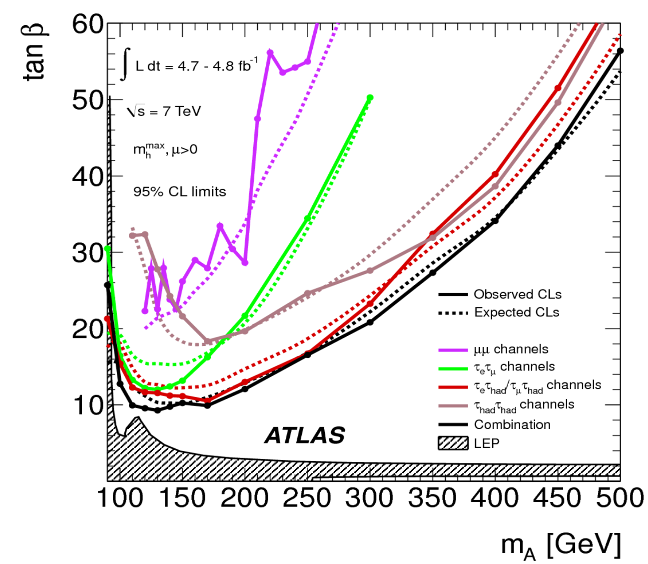
- Events categorized by tau decay mode: $\tau_e\tau_\mu$, $\tau_{lep}\,\tau_{had}$, $\tau_{had}\,\tau_{had}$, and further classified by presence or absence of a b-jet.
- $Z \rightarrow \tau\tau$ estimated from τ-embedded $Z \rightarrow \mu\mu$ events; multi-jet taken from same-sign data; other backgrounds scaled to data prediction in control regions.
- Final discriminant is di-tau invariant mass calculated with likelihood-based approach.



Neutral MSSM Higgs: Results





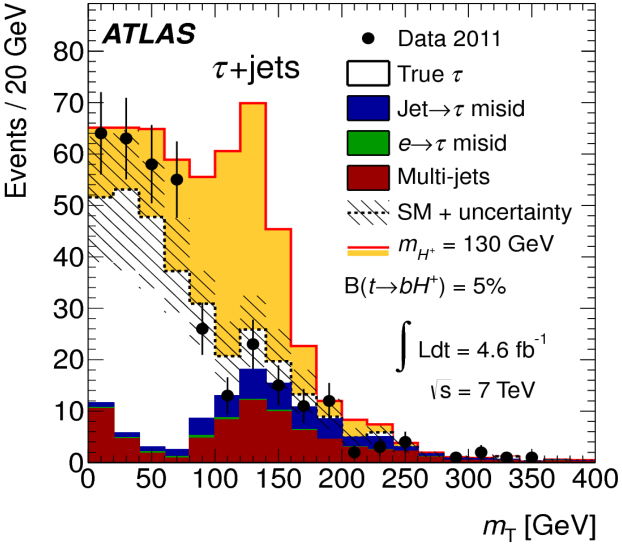


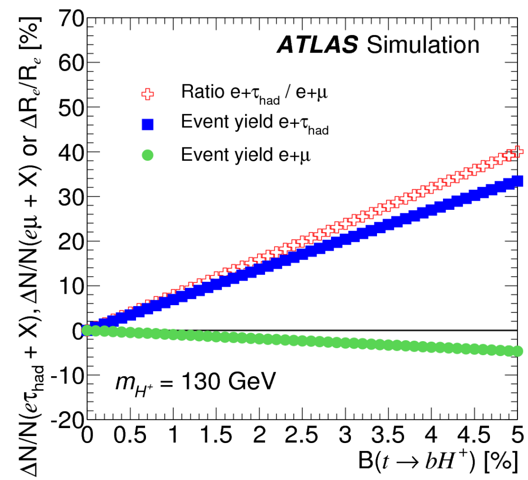
- No significant excess observed.
- Limits set on tanβ and on cross-section for a generic scalar boson.

$H^+ \rightarrow \tau\nu$: Analysis

arXiv:1212.3572
arXiv:1204.2760

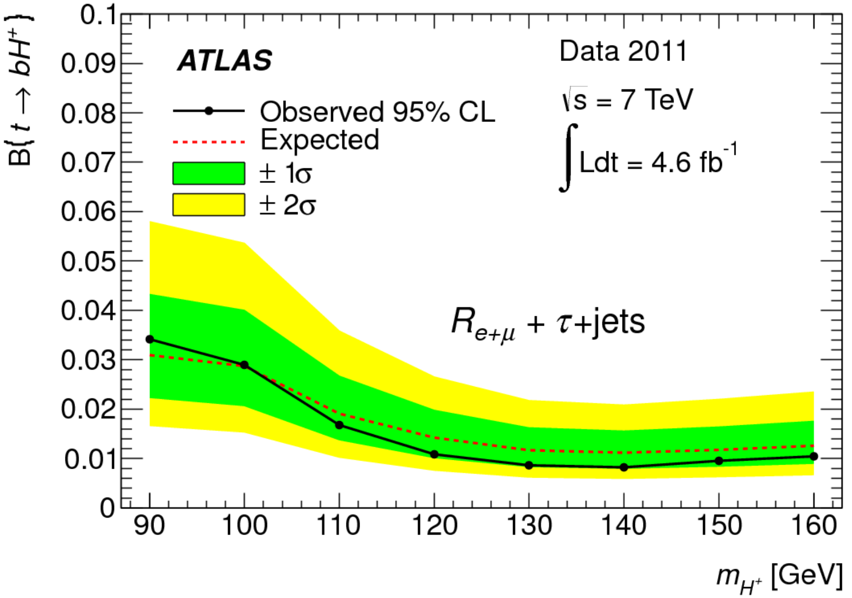
- Production occurs by $t\bar{t} \rightarrow bW\ bH^+$
- 2 analyses, depending on W/τ decays.
- τ + jets: W and τ decay hadronically. Apply tight MET cut, and window around top quark mass.
  - Final discriminant: m_T(tau, MET).
- Lepton Universality: W decays to e or μ, tau decays hadronically. Compare event yield to $t\bar{t}$ events with two light leptons.
  - Taking ratio allows for cancellation of major systematics.

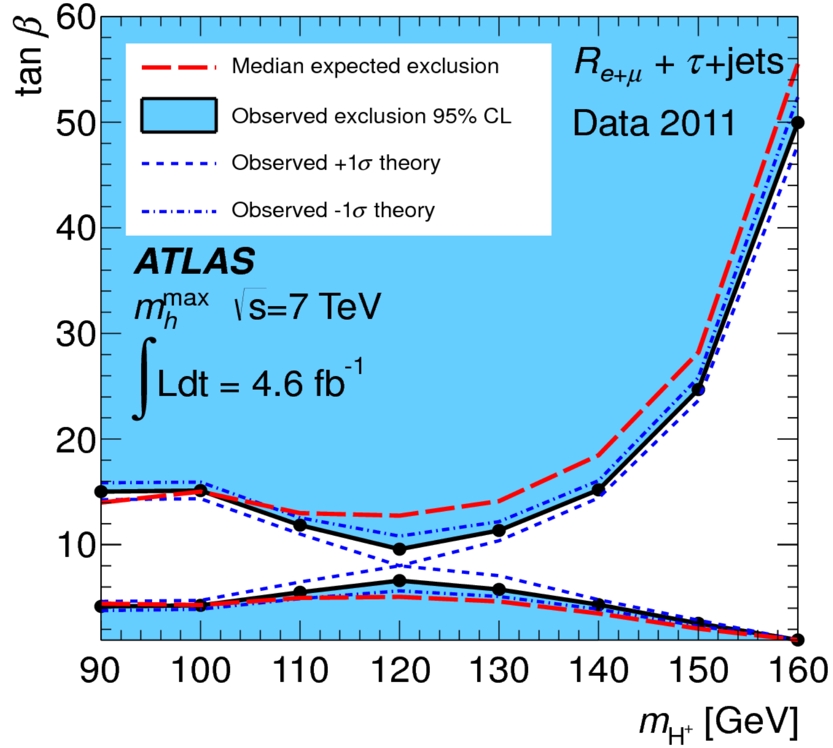




Ratio	R_e	R_μ
SM value	0.105 ± 0.012	0.166 ± 0.017
Measured value	0.115 ± 0.010 (stat)	0.165 ± 0.015 (stat)

$H^+ \to \tau\nu$: Results



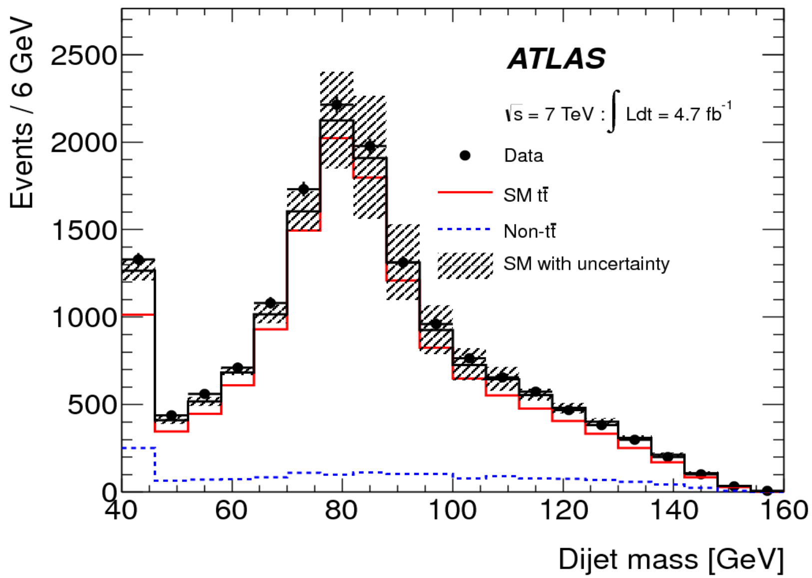


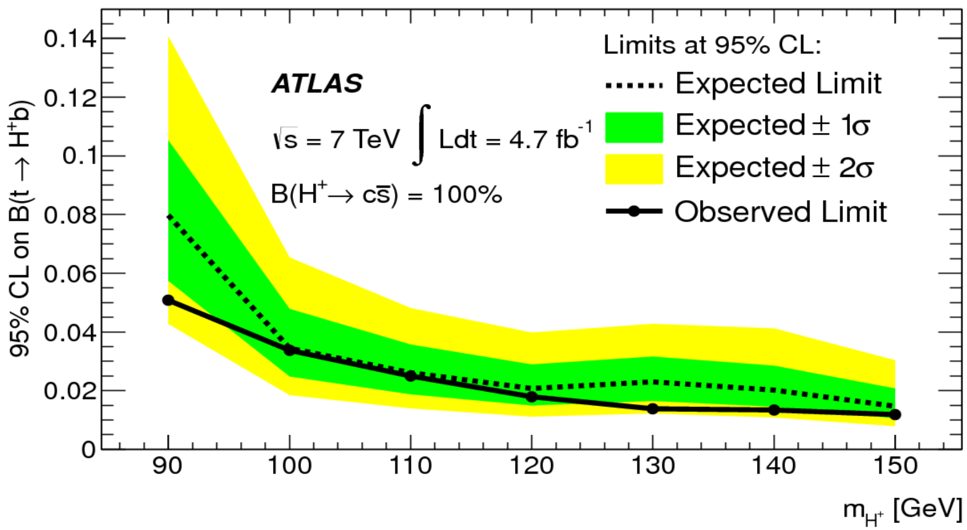
- No significant deviation is observed.
- Analyses combined to place limits on BR($t \to bH^+$), and on tanβ.
- Very little room remaining for a light charged Higgs boson!

$H^+ \rightarrow c\bar{s}$

arXiv:1302.3694

- Important decay mode for tanβ < 1.
- Semi-leptonic $t\bar{t}$ events are selected, and full event topology is reconstructed using a kinematic fitter.
- Di-jet invariant mass used as final discriminant.
- No excess observed; branching ratios $t \rightarrow H^+b$ above a few percent are excluded.





Conclusions

- Observation of one Higgs boson makes searching for others all the more important.
- No evidence for an extended Higgs sector has been seen.
- All of these searches, and many others, are being updated with the full Run 1 dataset.
- Exciting times are ahead of us: Stay Tuned!

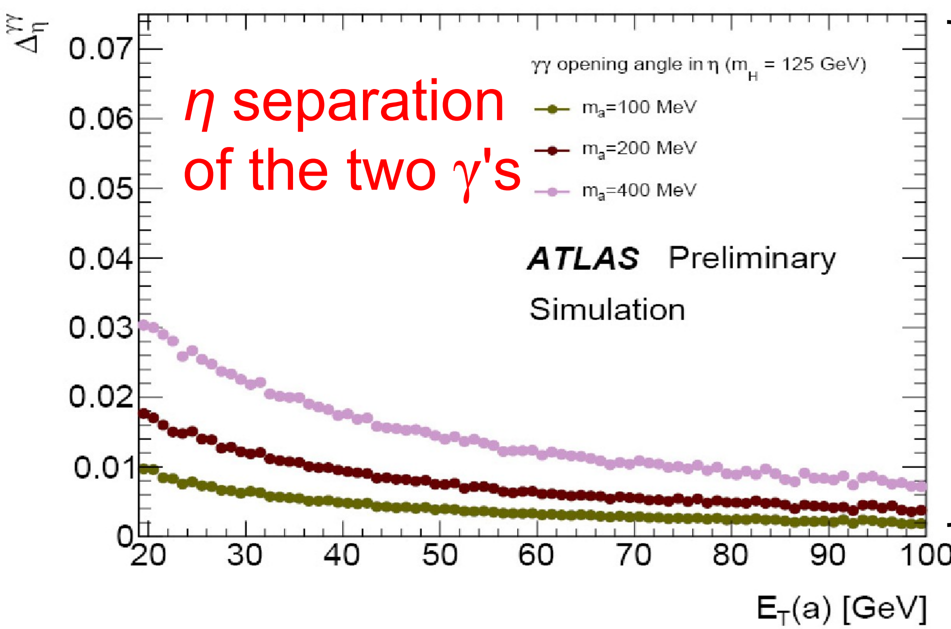
"We must never be afraid to go too far, for truth lies beyond."
-Marcel Proust

Beyond the Standard Slides

ATLAS-CONF-2012-079

$H \to aa \to 4\gamma$: Introduction

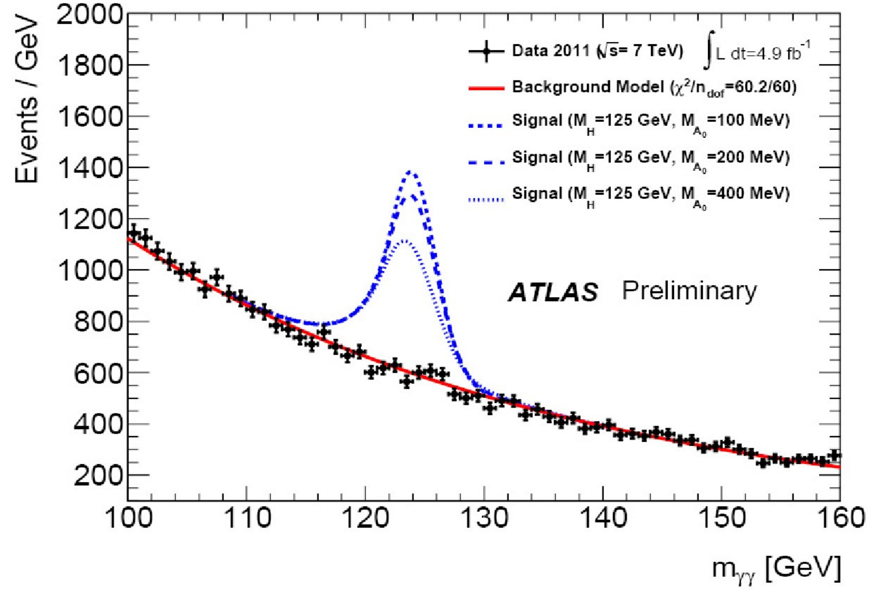
- Many BSM models (e.g. NMSSM) include a light, pseudoscalar Higgs boson *a*, produced directly or via heavy Higgs decays.
- If it is heavily boosted, decay products are tightly collimated
  - Two photons may appear as one!
- Events can enter standard $H \to \gamma\gamma$ analysis, but the selection is not optimal.

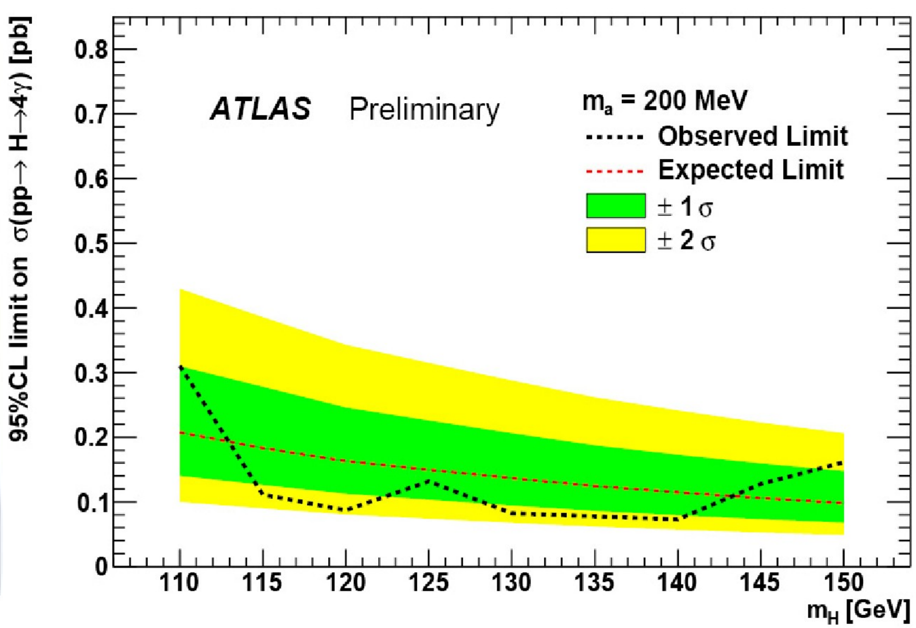


Width in η of an EM cluster for typical unconverted photons

$H \to aa \to 4\gamma$: Results

- Selection as in $H \to \gamma\gamma$, except:
  - Some shower-shape variables removed from photon ID
  - No event categorization applied
- Background fit to exponential



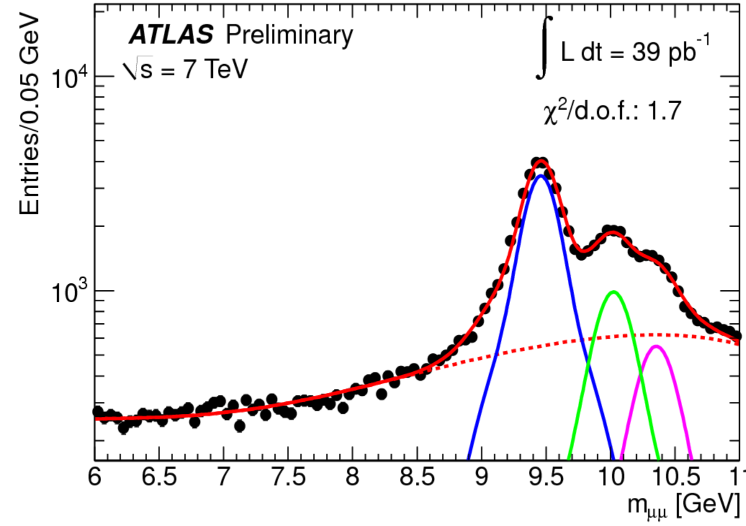


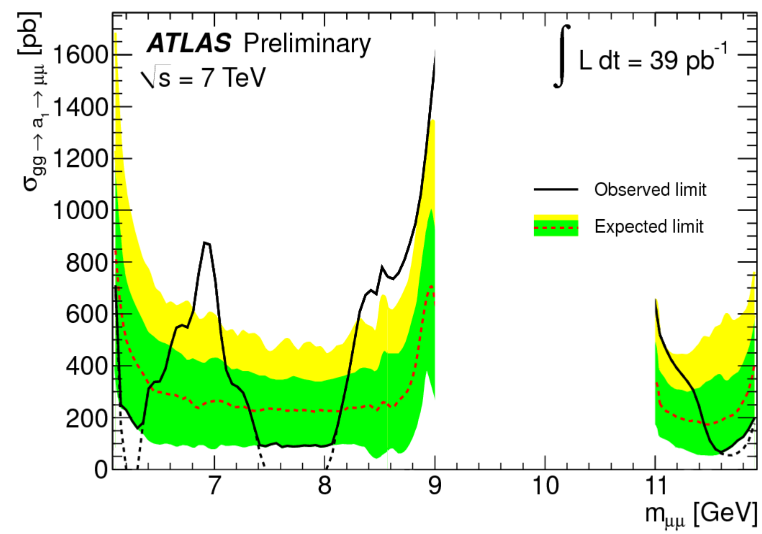
- No excess seen for these selection criteria.
- Limit on σ*BR set as a function of m_H.
  - Sensitivity decreases with higher m_a.

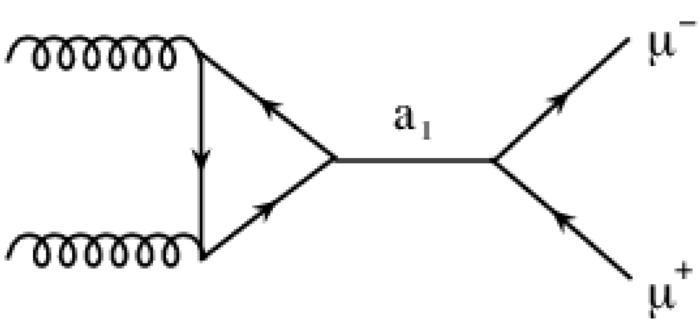
ATLAS-CONF-2011-020

NMSSM $a_1 \rightarrow \mu\mu$

- Direct production of light pseudo-scalar decaying to muons.
- Search for mass bump in the Υ sidebands (6-9 and 11-12 GeV).
- Multivariate selection to reject muons from hadronic decays.
- Background modelled with 4th order polynomail + 3 double-gaussians







2HDM: details

from Branco et. al.
arxiv:1106.0034

Model	u_R^i	d_R^i	e_R^i
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

	Type I	Type II	Lepton-specific	Flipped
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^ℓ	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
ξ_H^ℓ	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$
ξ_A^u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
ξ_A^d	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
ξ_A^ℓ	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

$H \to WW$: selection details

0-jet	2-jet
p_T(lep) > 25/15 GeV	
$m(l_1,l_2)$ > 15 GeV	
MET_{rel} > 25 GeV	
$\Delta\varphi(l_1,l_2)$ < 2.4	$\eta(j_1) \times \eta(j_2) < 0$
$m(l_1,l_2)$ < 75 GeV	$m(l_1,l_2)$ < 80 GeV
	m_T < 180 GeV

$$E_{\mathrm{T,rel}}^{\mathrm{miss}} = \begin{cases} E_{\mathrm{T}}^{\mathrm{miss}} \sin(\Delta\phi_{\mathrm{min}}) & \text{if } \Delta\phi_{\mathrm{min}} < \pi/2 \\ E_{\mathrm{T}}^{\mathrm{miss}} & \text{if } \Delta\phi_{\mathrm{min}} \geq \pi/2 \end{cases}$$

$$m_{\mathrm{T}} = \sqrt{(E_{\mathrm{T}}(\ell_1\ell_2) + E_{\mathrm{T}}(\nu\nu))^2 - (\vec{p}_{\mathrm{T}}(\ell_1\ell_2) + \vec{E}_{\mathrm{T}}^{\mathrm{miss}})^2}$$

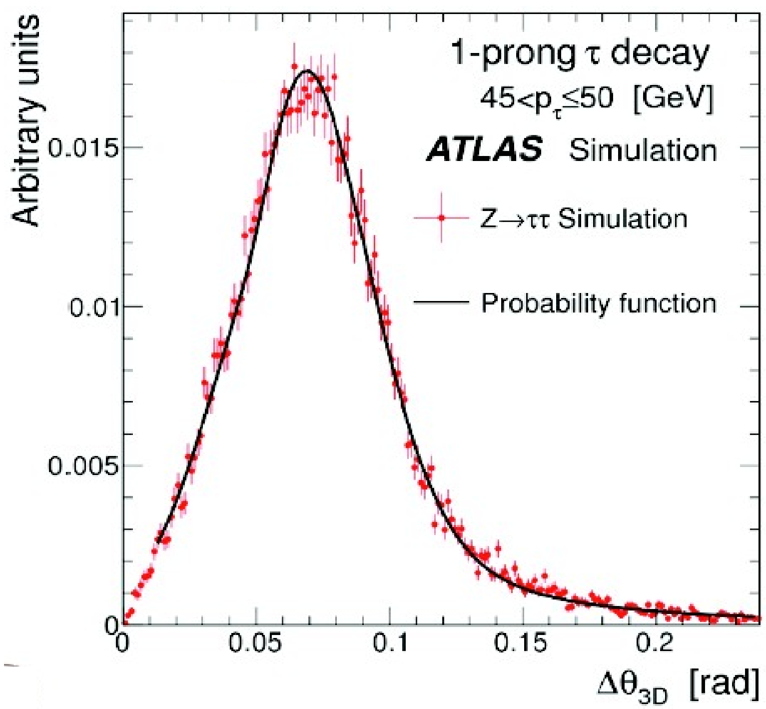
MSSM Higgs → ττ: Cut details

Channel	$\tau\tau \to e\mu$	$\tau\tau \to e\tau_h$ / $\mu\tau_h$	$\tau\tau \to \tau_h\tau_h$
Pre-selection	**-Opposite-sign e & μ** **-m(e,μ) > 30 GeV** **-Δφ(e,μ) > 2.0** **-MET+p_T(e)+p_T(μ) < 125 GeV** **-ΣcosΔφ(l,MET) > -0.2**	**-Opposite-sign l & τ_h** **-No additional leptons** **-m_T(l,MET) < 30 GeV**	**-Two opposite-sign τ_h** **-No light leptons** **-MET > 25 GeV**
b-tagged	**-Exactly 1 b-jet** **-Σp_T(jets) < 100 GeV**	**-Leading jet b-tagged** **-p_T(b-jet) < 50 GeV**	**-Leading jet b-tagged** **-p_T(b-jet) < 50 GeV**
no b-tag	**-0 b-tagged jets** **-Σp_T(jets) < 150 GeV**	**-Lead jet fails b-tag** **-MET > 20 GeV**	**-Lead jet fails b-tag** **-Lead τ_h p_T > 60 GeV**

The Missing Mass Calculator

- 4 constraints on mass of di-tau system, but 6-8 unknowns
  - Depending on # of neutrinos in final state

$$
\begin{aligned}
E_x^{\text{miss}} &= p_{\text{miss}_1} \sin\theta_{\text{miss}_1} \cos\phi_{\text{miss}_1} + p_{\text{miss}_2} \sin\theta_{\text{miss}_2} \cos\phi_{\text{miss}_2}, \\
E_y^{\text{miss}} &= p_{\text{miss}_1} \sin\theta_{\text{miss}_1} \sin\phi_{\text{miss}_1} + p_{\text{miss}_2} \sin\theta_{\text{miss}_2} \sin\phi_{\text{miss}_2}, \\
m_\tau^2 &= m_{\text{miss}_1}^2 + m_{\text{vis}_1}^2 + 2\sqrt{p_{\text{vis}_1}^2 + m_{\text{vis}_1}^2}\sqrt{p_{\text{miss}_1}^2 + m_{\text{miss}_1}^2} \\
&\quad -2 p_{\text{vis}_1} p_{\text{miss}_1} \cos\Delta\theta_{\text{vm}_1}, \\
m_\tau^2 &= m_{\text{vis}_2}^2 + 2\sqrt{p_{\text{vis}_2}^2 + m_{\text{vis}_2}^2} \cdot p_{\text{miss}_2}, \\
&\quad -2 p_{\text{vis}_2} p_{\text{miss}_2} \cos\Delta\theta_{\text{vm}_2}
\end{aligned}
$$



- Ambiguity resolved by scanning the parameter space, calculating the mass for each point, weighting the solution by the likelihood to come from a tau decay.
- Final MMC mass is the peak of the resulting distribution.

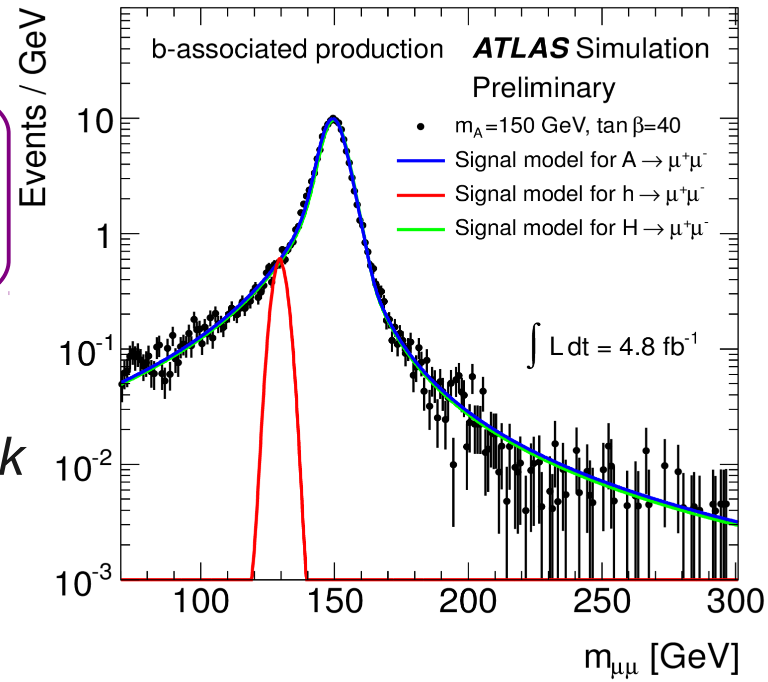
A.Elagin, P.Murat, A.Pranko, A.Safonov
arXiv:1012.4686 ; NIM A654 (2011) 481

Signal Modelling in MSSM μμ

- Simulated signal points parametrized by Breit-Wigner convoluted with a gaussian, plus a Landau for the asymmetric tail.
- Signal model is different for each point in the m_A-tanβ plane, but can only produce MC for a limited number.
- Intermediate signal models obtained by interpolating the fit parameters from simulated points.

$$N\left[\frac{1}{\left[x^2-M^2\right]^2+M^2\Gamma^2}\otimes f_{Gauss}(x,\sigma)+c f_{Landau}(-x,M,\varsigma)\right]$$

Comparison of simulated signal (black points) with the model obtained from interpolation (blue line)



Charged Higgs: Details

- ATLAS has employed 2 strategies in the $H^+ \rightarrow \tau\nu$ search:
  - Direct search (arXiv:1212.3572)
  - Lepton Universality (arXiv:1204.2760)
- The direct search is broken into 3 sub-channels:
  - $t\bar{t} \rightarrow b\bar{b}H^{\pm}W \rightarrow b\bar{b}(\tau_{lep}\,\upsilon)(q\bar{q})$: "lepton + jets"
  - $t\bar{t} \rightarrow b\bar{b}H^{\pm}W \rightarrow b\bar{b}(\tau_{had}\,\upsilon)(l\upsilon)$: "tau + lepton"
  - $t\bar{t} \rightarrow b\bar{b}H^{\pm}W \rightarrow b\bar{b}(\tau_{had}\,\upsilon)(q\bar{q})$: "tau + jets"
- Of these, tau + lepton and lepton + jets are not orthogonal to the selection used by the Lepton Universality method.
- Therefore tau + jets may be combined either with these channels or the Lepton Universality analysis, but not both.

Direct H^+: Selection

Lepton + Jets

- 1 e or μ
- 4 or more jets (2 b-tagged)
- MET > 40 GeV
  - Tighter at small $\Delta\varphi(l,\text{MET})$
- $\cos\theta_l^* < -0.6$
- $m_T(l,\text{MET}) < 60$ GeV

$$\cos\theta_l^* = \frac{2m_{bl}^2}{m_{\text{top}}^2 - m_W^2} - 1 \simeq \frac{4\,p^b \cdot p^l}{m_{\text{top}}^2 - m_W^2} - 1$$

Tau + Lepton

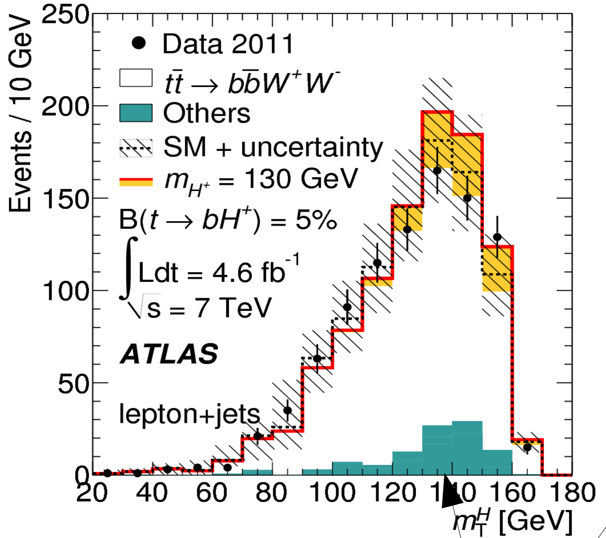
- 1 e or μ, 1 opposite-sign τ
- 2 or more jets ($\geq$1 b-tagged)
- Σp_T(tracks) > 100 GeV

Tau + Jets

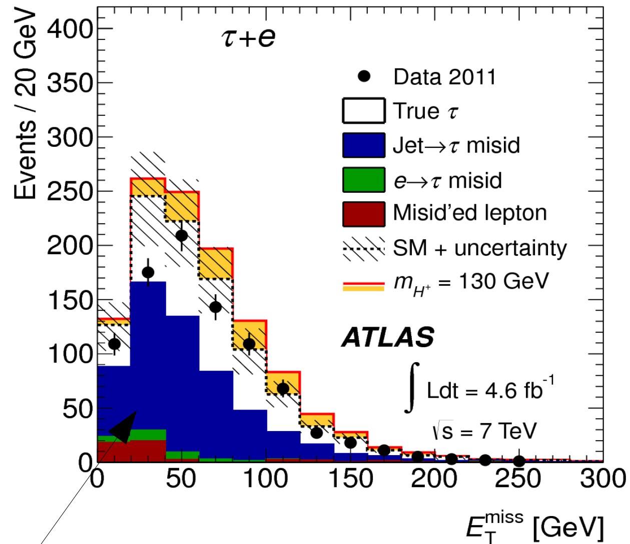
- Exactly 1 τ, no other leptons
- 4 or more jets ($\geq$1 b-tagged)
- MET > 65 GeV
  - Tighter at high Σp_T(tracks)
- $120 < m_{jjb} < 240$ GeV

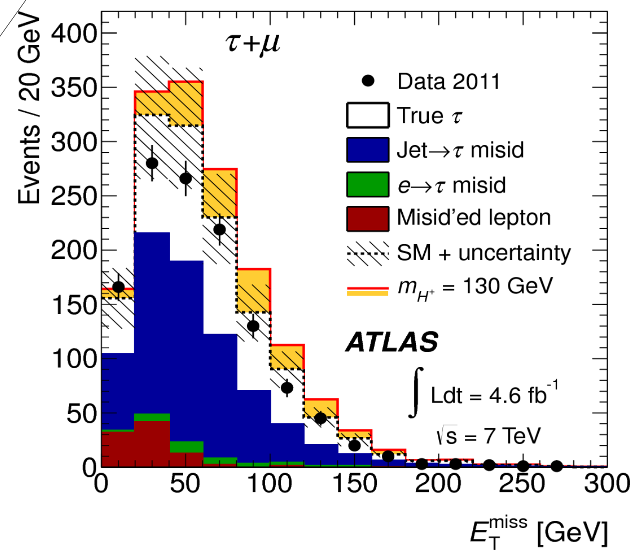
Direct H+: Distributions

Lepton + jets

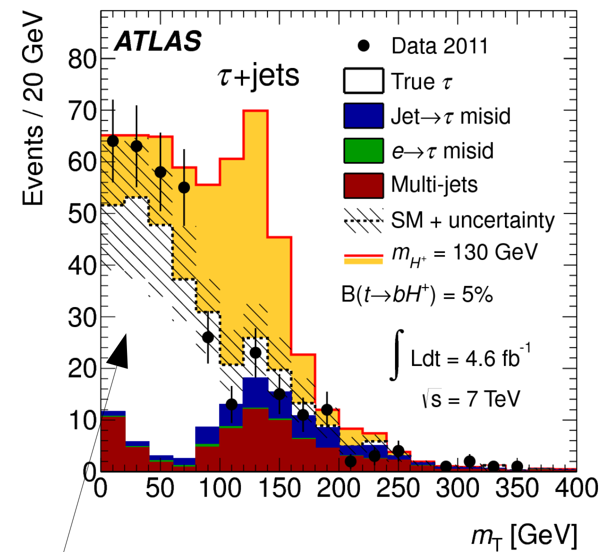


Tau + lepton





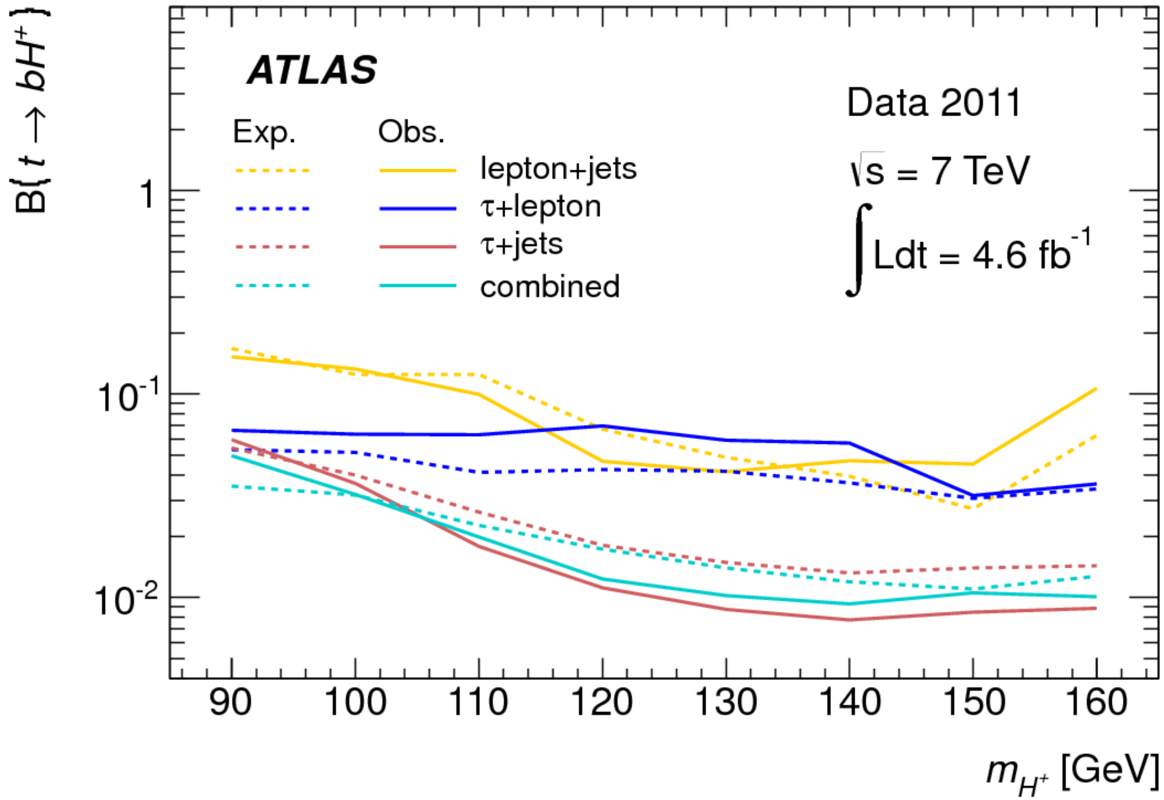
Tau + jets



Mis-identified taus & leptons scaled from data

True tau contribution taken from "embedding"

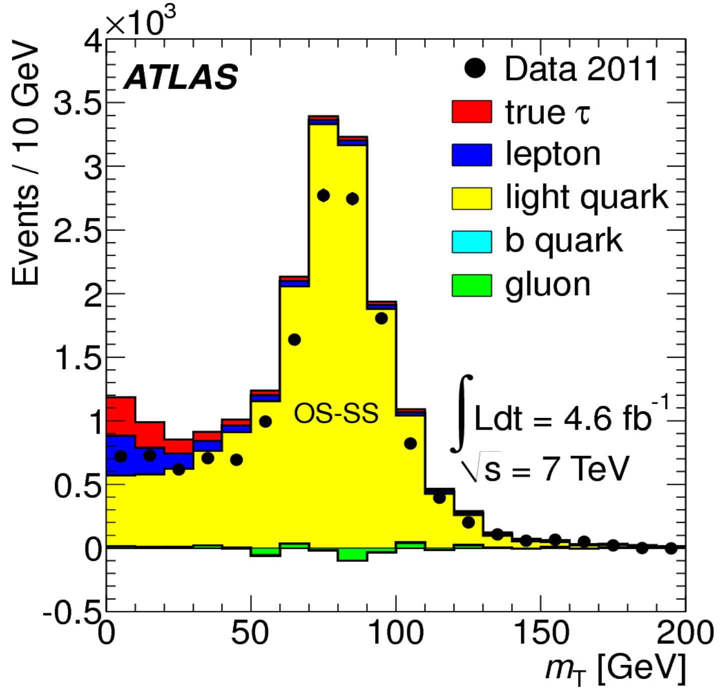
Direct H+: Limits



Lepton Universality: selection

- Single electron or single muon trigger, and trigger-matched lepton with $p_T > 25$ GeV.
- At least 2 jets including exactly 2 b-tags
- One additional τ or light lepton of different flavor.
- MET > 40 GeV.

Events with fake taus normalized using W-enriched region, with same-sign events subtracted.



Lepton Universality: results

Ratio	R_e	R_μ
SM value	0.105 ± 0.012	0.166 ± 0.017
Measured value	0.115 ± 0.010 (stat)	0.165 ± 0.015 (stat)

$$R_e = \frac{\mathcal{N}(e + \tau_{\text{had}})}{\mathcal{N}(e+\mu)} \quad \text{and} \quad R_\mu = \frac{\mathcal{N}(\mu + \tau_{\text{had}})}{\mathcal{N}(\mu+e)}$$