Search for BSM Higgs Bosons at ATLAS

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on behalf of the ATLAS collaboration

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BMBF-Forschungsschwerpunkt
ATLAS Experiment
Physics on the TeV-scale at the Large Hadron Collider

FSP 101 ATLAS

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

hep-ph/0608079v1

- MSSM neutral $h/H/A \to \tau\tau$
- Charged Higgs bosons

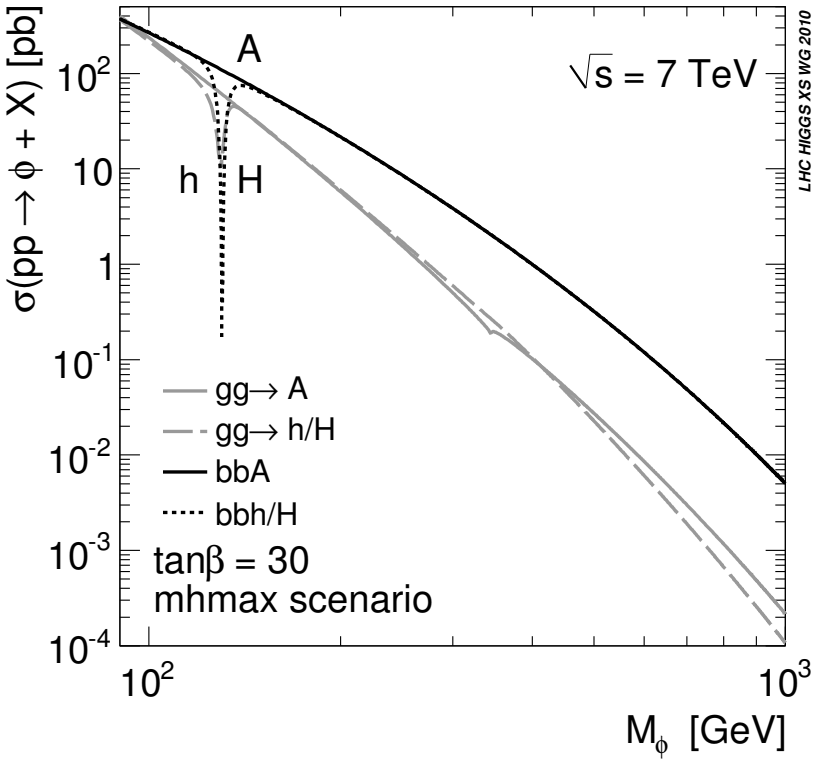
$$H^+ \to \tau_{\rm had}\nu$$
$$H^+ \to \tau_{lep}\nu$$
$$H^+ \to c\bar{s}$$

- Fermiophobic $H \to \gamma\gamma$
- Doubly charged Higgs $H^{++} \to \mu^+\mu^+$
- NMSSM $a_1 \to \mu\mu$

MSSM $h/A/H \to \tau\tau$ (ATLAS-CONF-2011-132) $1.06\,\mathrm{fb}^{-1}$

MSSM Higgs sector

- 5 Higgs bosons: h, H (CP=+1) A (CP=-1), $H^{\pm}$
- soft breaking parameters fixed in benchmark scenarios (e.g. m_h^{max}), keeping dependence on $m_A, \tan\beta$
- medium/high $\tan\beta$:
  - b-quark associated production and gluon-gluon-fusion
  - almost no decays to WW/ZZ, $\approx$ 90% $b\bar{b}$, 10% $\tau\tau$



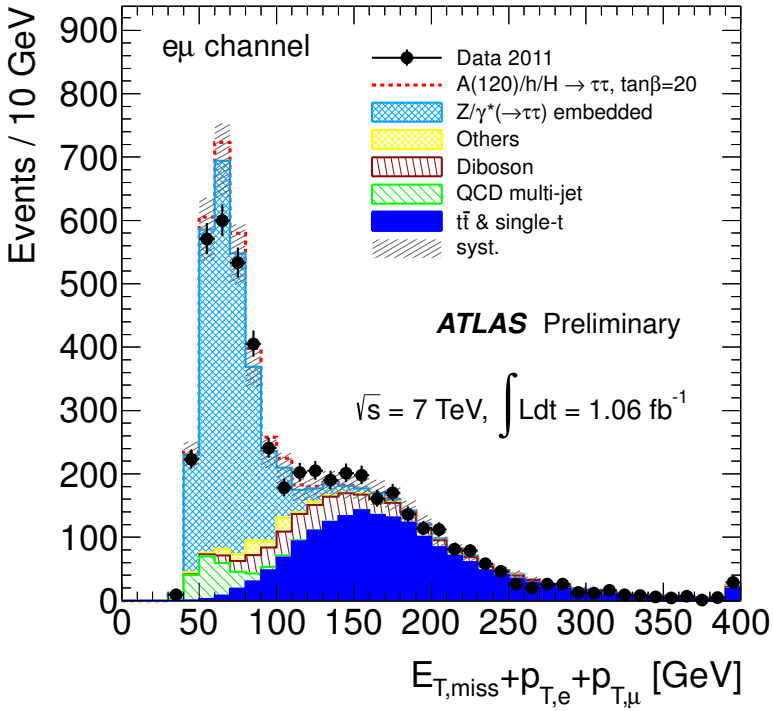
Analyzed channels	BR
$\tau\tau \to e\mu + 4\nu$	6%
$\tau\tau \to e/\mu\tau_{\mathrm{had}} + 3\nu$	46%
$\tau\tau \to \tau_{\mathrm{had}}\tau_{\mathrm{had}} + 2\nu$	42%

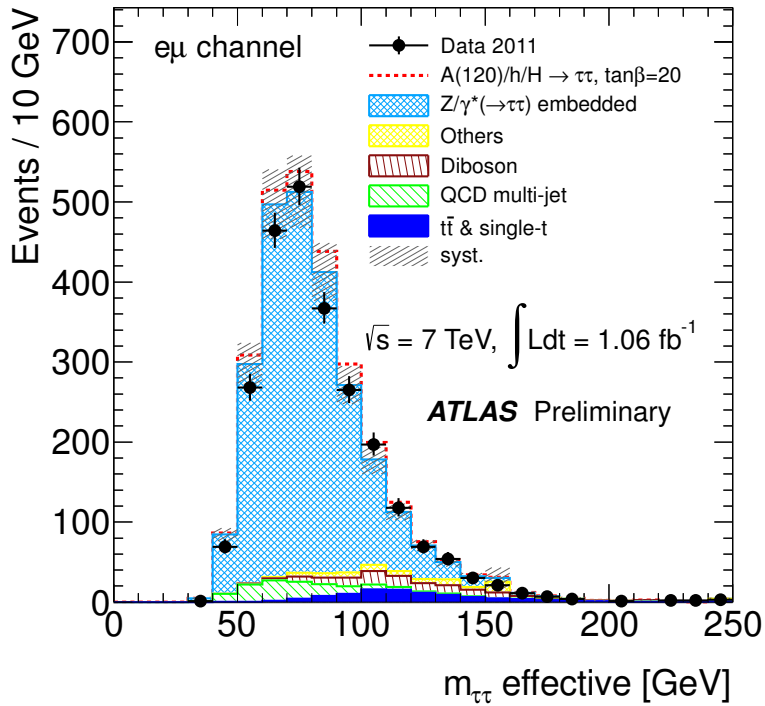
$e\mu$ channel

- 1 e, 1 μ, isolation, $q_e = -q_\mu$
- cuts against $t\bar{t}$, diboson:
  - $\Delta\Phi_{e\mu} > 2.0$ rad,
  - $p_{\mathrm{T}}^{e} + p_{\mathrm{T}}^{\mu} + E_{\mathrm{T}}^{\mathrm{miss}} < 120$ GeV
- 90% $Z \to \tau\tau$: embeddding technique from $Z \to \mu\mu$
- 5% QCD multi-jet: estimated from control regions
- remaining 5% from simulation
- use effective mass:

$$m_{\tau\tau}^{\mathrm{eff.}} = \sqrt{(p_e + p_\mu + p_{E_{\mathrm{T}}^{\mathrm{miss}}})^2}$$

Data	2471
Backgrounds	2600 ± 200
Signal ($m_A = 120$ GeV, $\tan\beta = 20$, m_h^{max})	155 ± 6

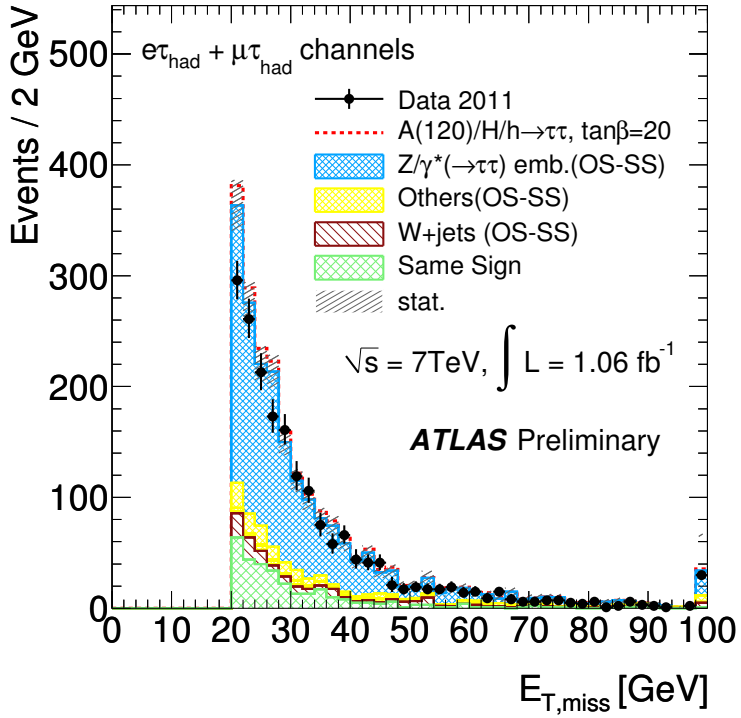


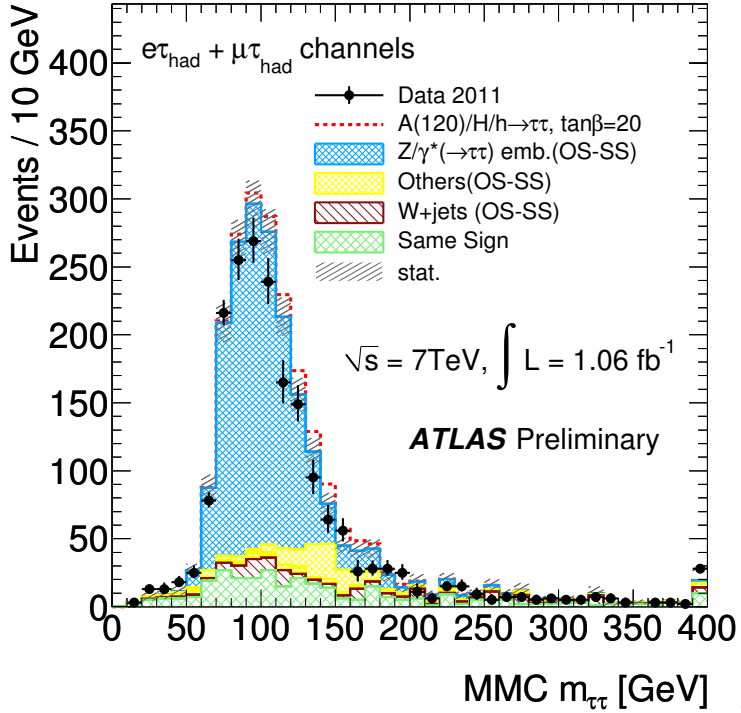


$e/\mu\tau_{\rm had}$ channels

- 1 e or 1 μ, 1 identified hadronic τ, opposite electric charge
- $E_{\rm T}^{\rm miss} > 20$ GeV (vs. QCD, $Z \to \ell\ell$)
- $m_T(\ell, E_{\rm T}^{\rm miss}) < 30$ GeV (vs. $W \to \ell\nu$)
- veto on double leptons
- $\approx 70\%$ $Z \to \tau\tau$: embedding
- QCD and W+jets: estimate from same-sign control region
- use Missing Mass Calculator (MMC)(NIM A654 (2011) 481)

	$e\tau_{\rm had}$	$\mu\tau_{\rm had}$
Data	626	1287
Backgrounds	775 ± 40	1378 ± 43
Signal ($m_A = 120$ GeV, $\tan\beta = 20$, m_h^{max})	41 ± 4	75 ± 5

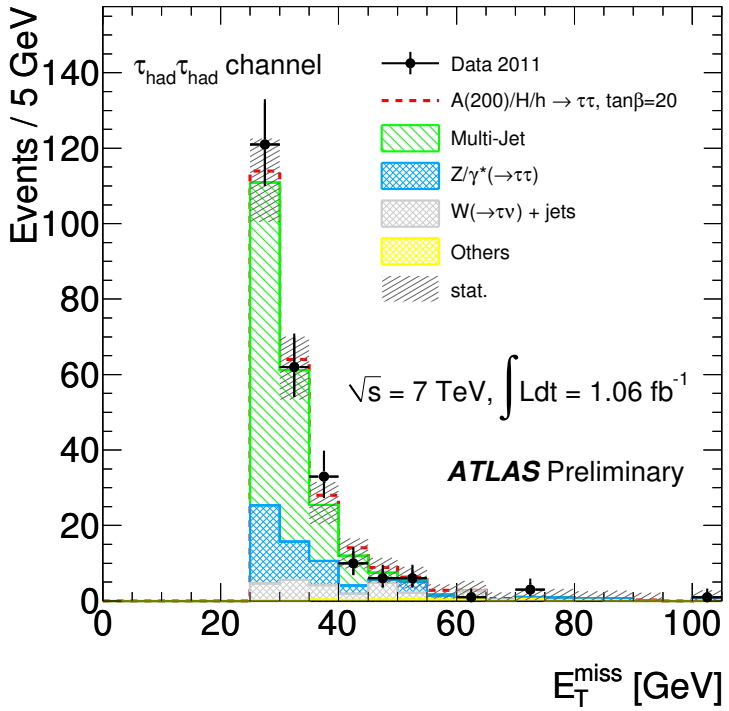


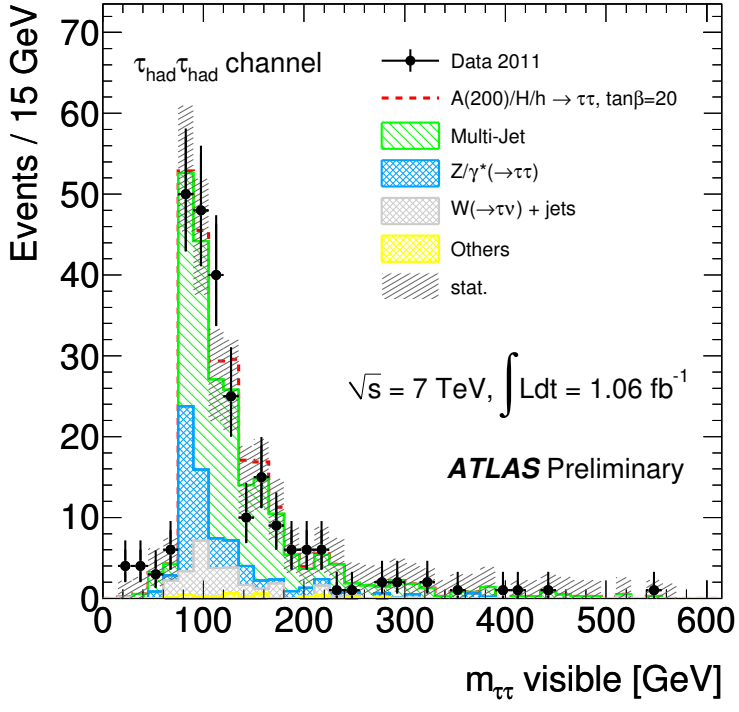


$\tau_{\text{had}}\tau_{\text{had}}$ channel

- two identified hadronic τ's
- $E_{\text{T}}^{\text{miss}} > 25$ GeV vs. QCD and Z
- veto on events with electron or muon
- dominant QCD background estimated from control regions
- $Z \to \tau\tau$ and $W \to \tau\nu$ from simulation, validated with embedding technique
- use visible mass $m_{\tau_{\text{had}}\tau_{\text{had}}}$

Data	245
Backgrounds	233^{+44}_{-28}
Signal ($m_A = 200$ GeV, $\tan\beta = 20$, m_h^{max})	19 ± 1





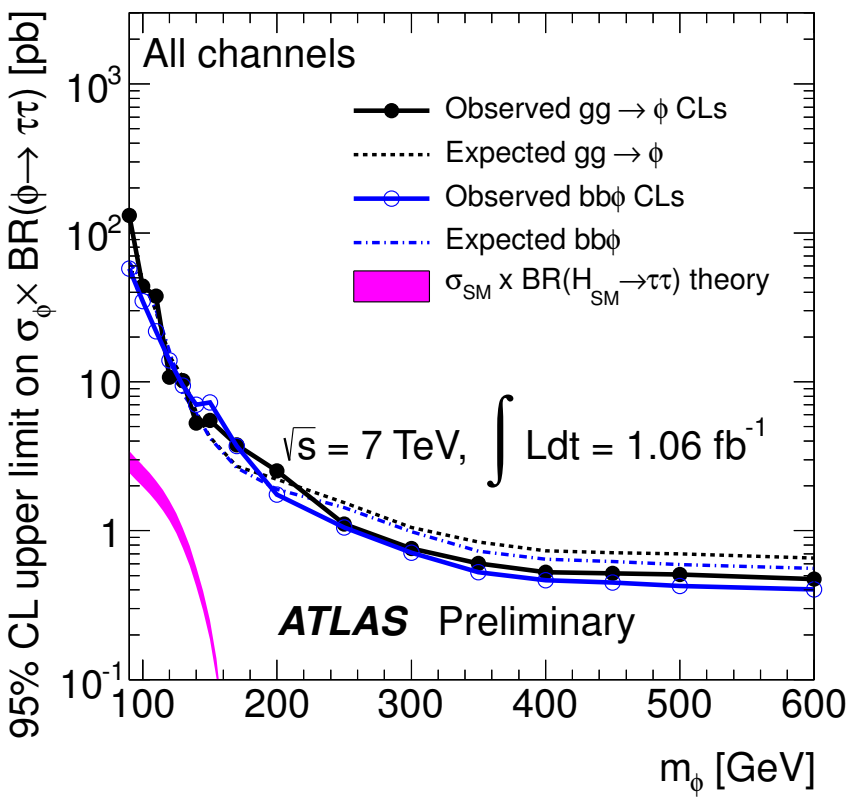
MSSM $h/A/H \to \tau\tau$: Limits

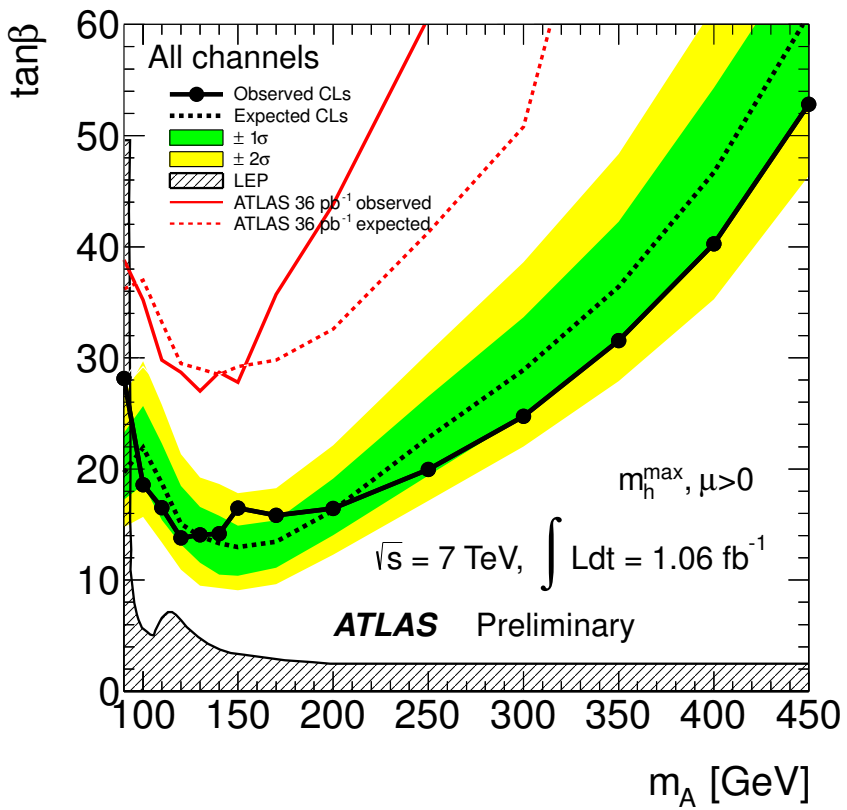
$\sigma \times BR(\phi \to \tau\tau)$

- assume only one resonance:
  - 100% $gg \to \phi$ or 100% $b\bar{b}\phi$ (acceptances slightly different)
- useful to test arbitrary models

$(m_A, \tan\beta)$-plane

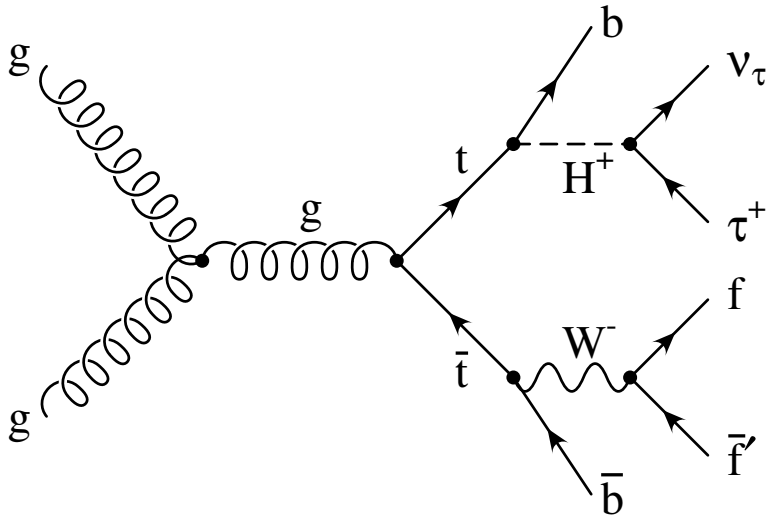
- have to assume specific (c)MSSM scenario
- here: m_h^{max}-scenario

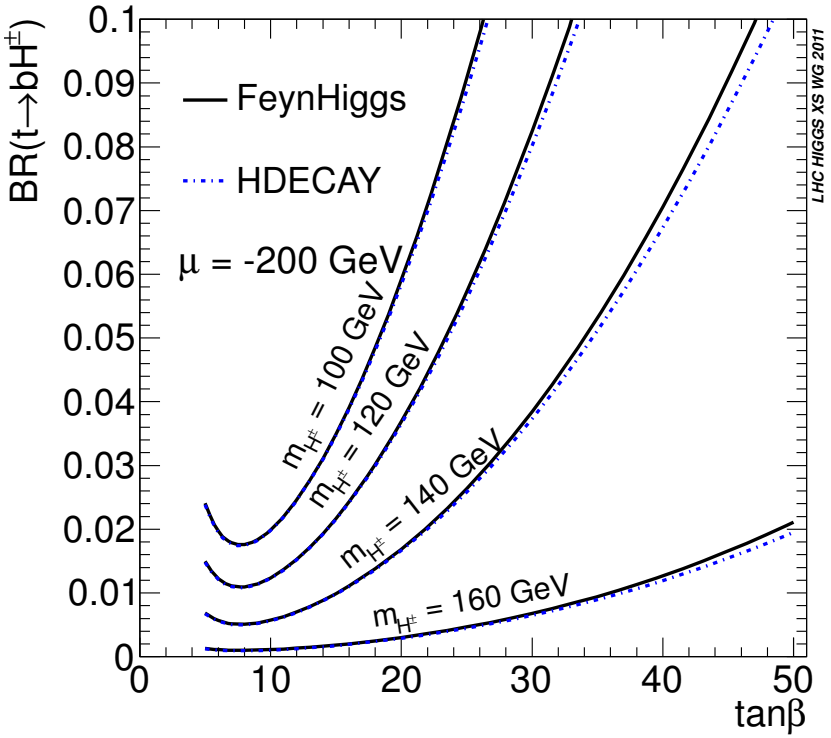




Charged Higgs bosons

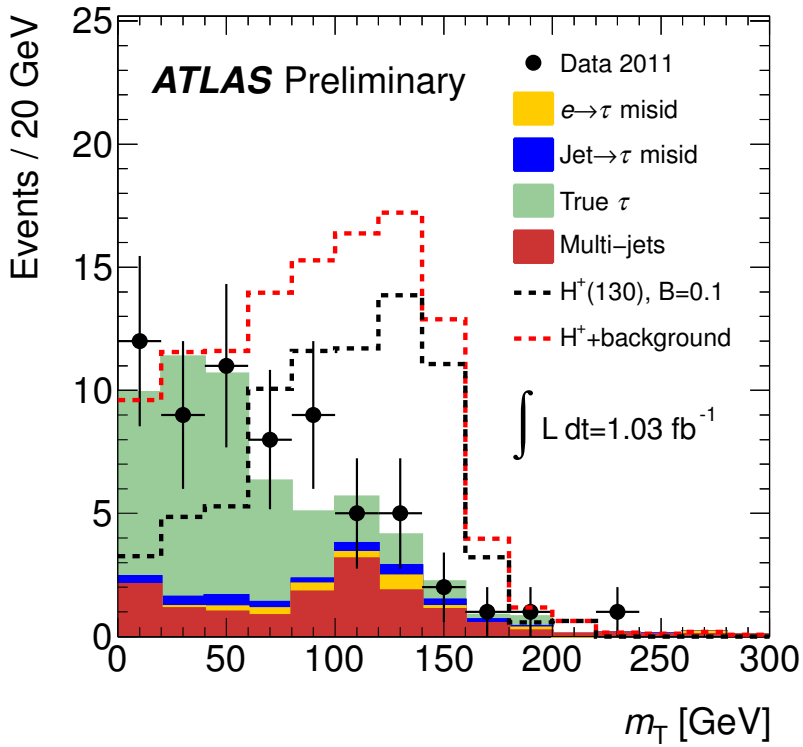
- predicted in Higgs doublet (e.g. MSSM) and triplet models
- $m_{H^+} < m_t$: produced predominantly in top quark decays
- $\tan\beta > 3 \Rightarrow$ decays to $\tau\nu$ preferred
- heavy H^+: $gb \to tH^+$ important, more data needed





τ_{had} channel ($W \to q\bar{q}'$, $H^+ \to \tau_{\mathrm{had}}\nu$)

- 1 identified hadronic τ ($p_{\mathrm{T}} > 35$ GeV), veto on identified electrons and muons
- missing transverse energy
- at least 4 jets, ≥ 1 b-tagged
- final discriminant: $m_T(\tau_{\mathrm{had}}, E_{\mathrm{T}}^{\mathrm{miss}})$
- background with true τ-leptons from data: $t\bar{t} \to \mu$+jets and embedding technique
- $e \to \tau$ and jet$\to \tau$ misidentification by applying measured misd. probabilities to simulation
- multi-jet (no real $E_{\mathrm{T}}^{\mathrm{miss}}$): fit of $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution to data

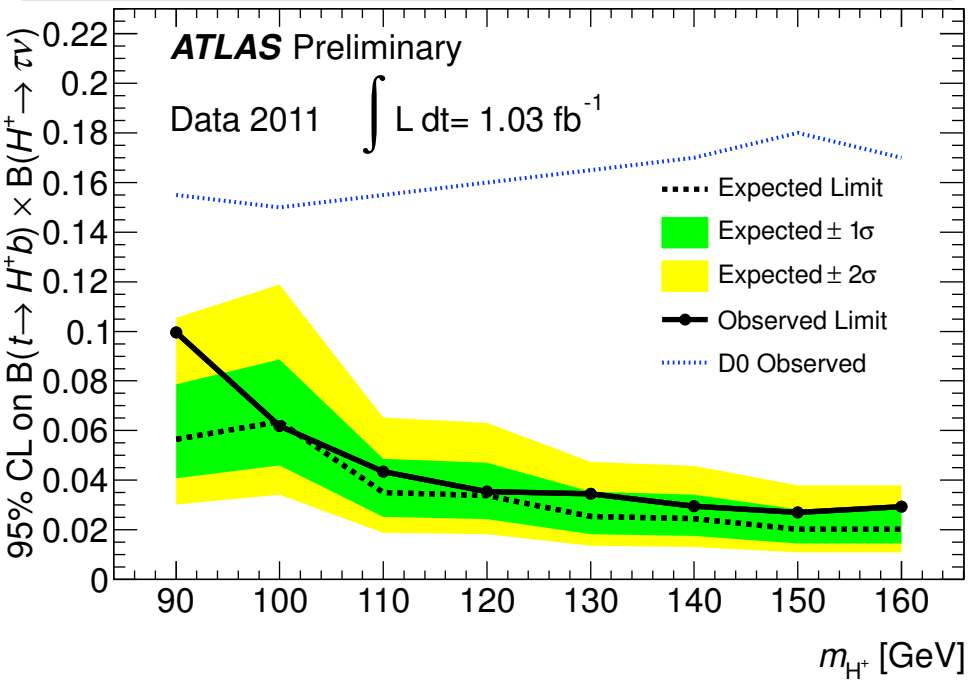


Limits for $H^+ \to \tau_{\mathrm{had}}\nu$ channel

- Observation compatible with background expectation

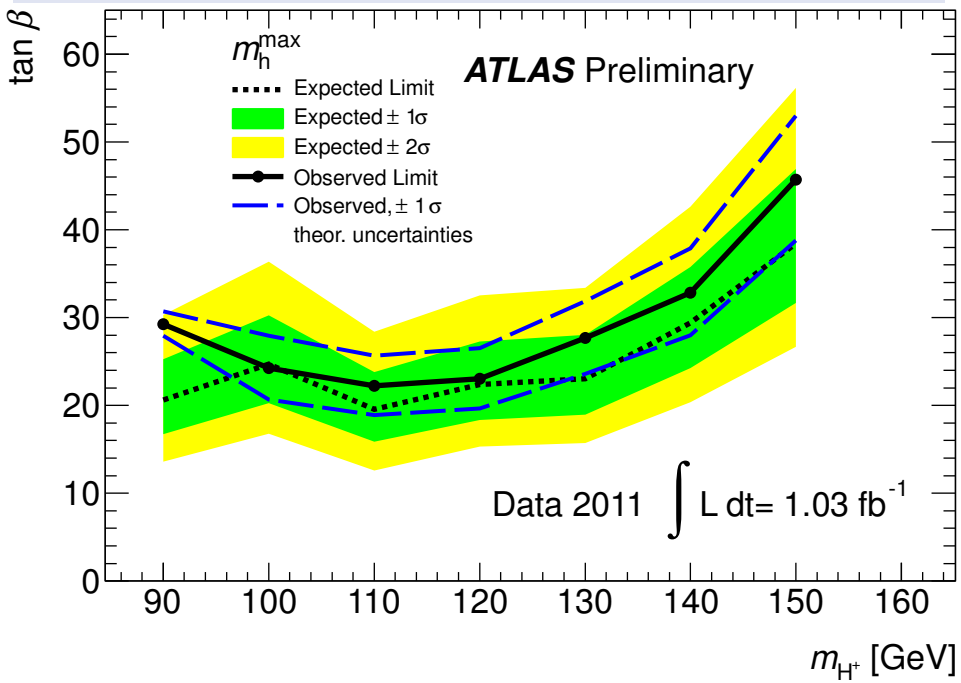
Model independent

- place limit on $BR(t \to H^+b) \times BR(H^+ \to \tau\nu)$
- can be compared to any model!



MSSM Interpretation

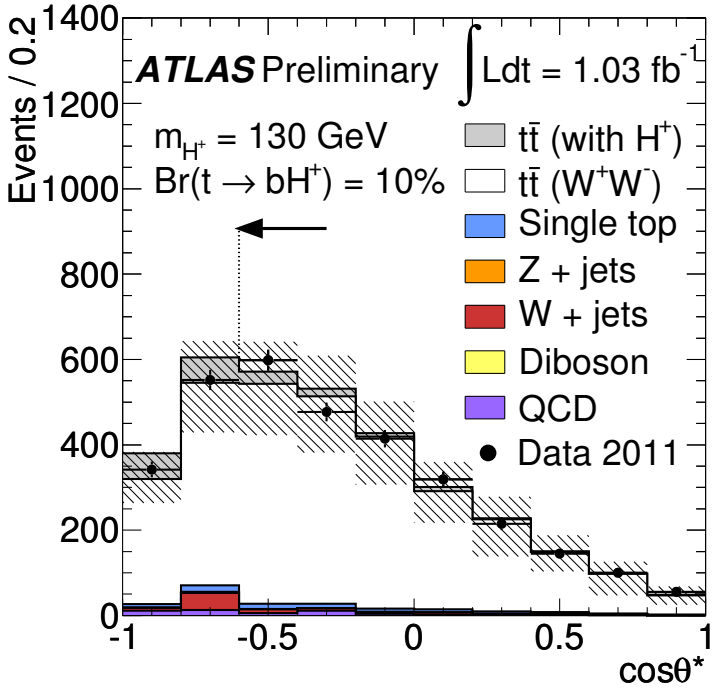
- assume specific (c)MSSM model, here: m_h^{max}
- limit in $(m_{H^+}, \tan\beta)$-plane

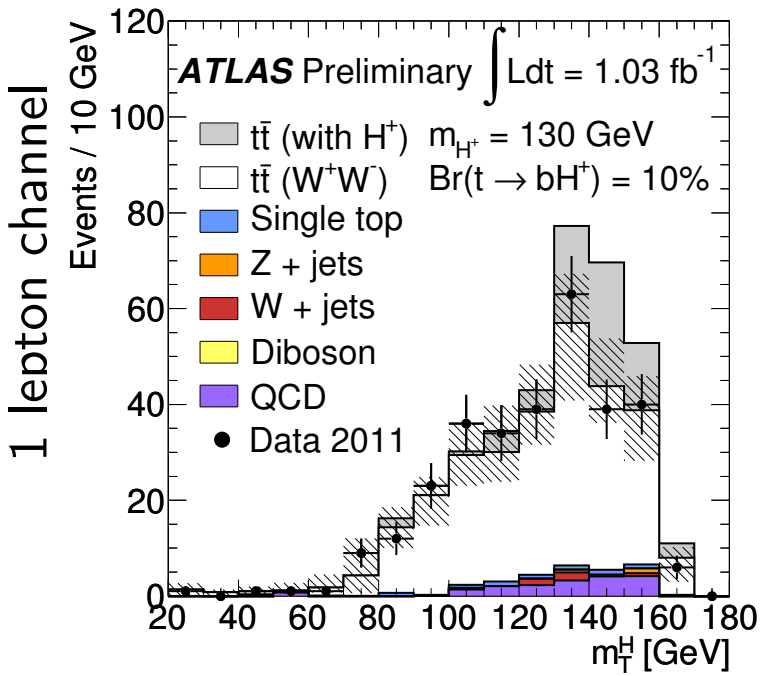


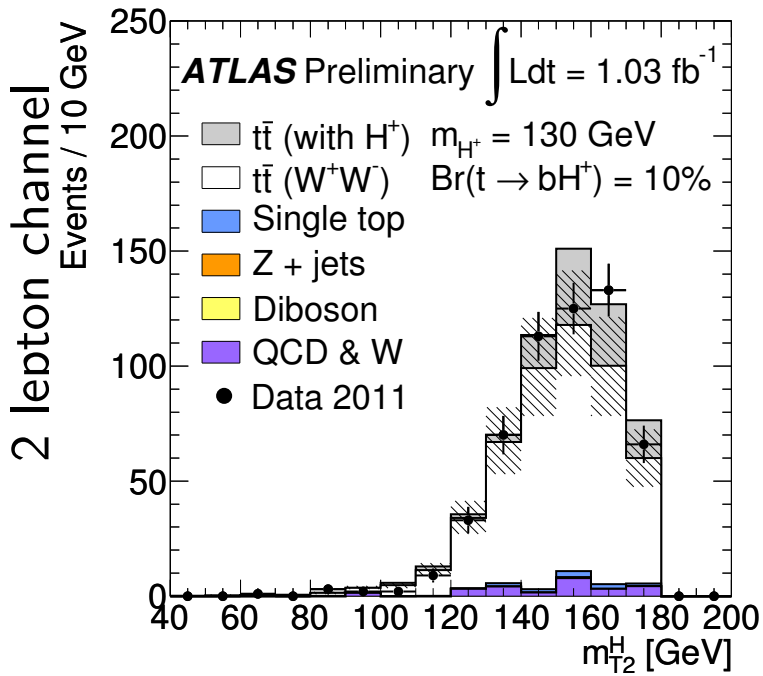
τ_{lep} channels $H^+ \to \tau_{\text{lep}}\nu, W \to q\bar{q}'$ or $\ell\nu$

- common technique: introduce new variable $\cos\theta_l^* = \frac{2m_{bl}^2}{m_{\text{top}}^2 - m_W^2} - 1$
- constrain $t\bar{t} \to b\bar{b}W^+W^-$ contribution (cannot rely on theory) from control region with large $\cos\theta_l^*$, signal region: small $\cos\theta_l^*$
- final discriminants: transverse masses m_T^H, m_{T2}^H (Phys. Rev. D 81 (2010) 055010)

example for 1 lepton channel





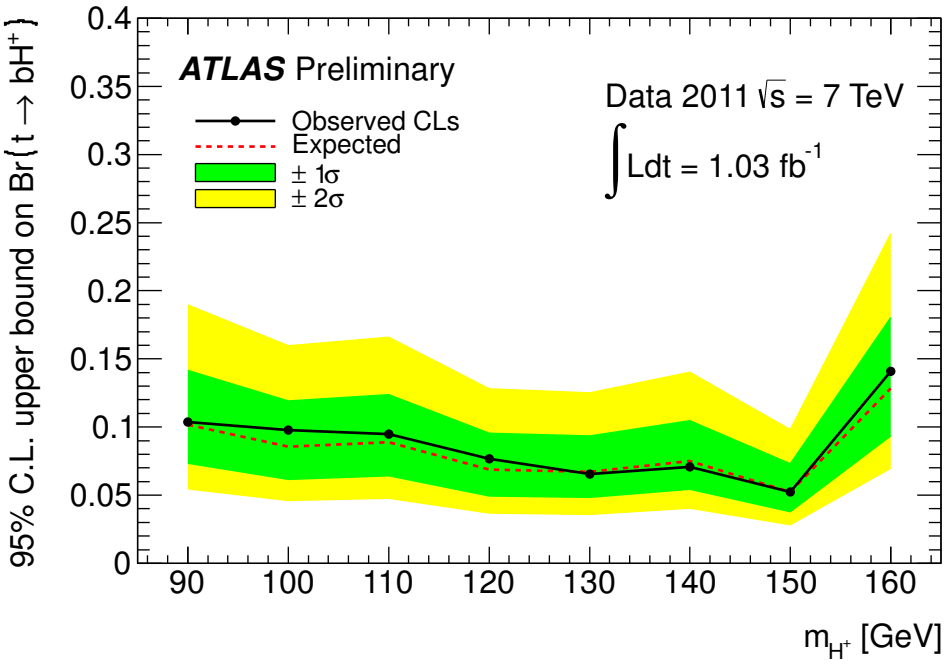


Limits for leptonic channels, $H^+ \to \tau_{\mathrm{lep}}\nu, W \to q\bar{q}/\ell\nu'$

- Observation compatible with background expectation $\Rightarrow$ set limits

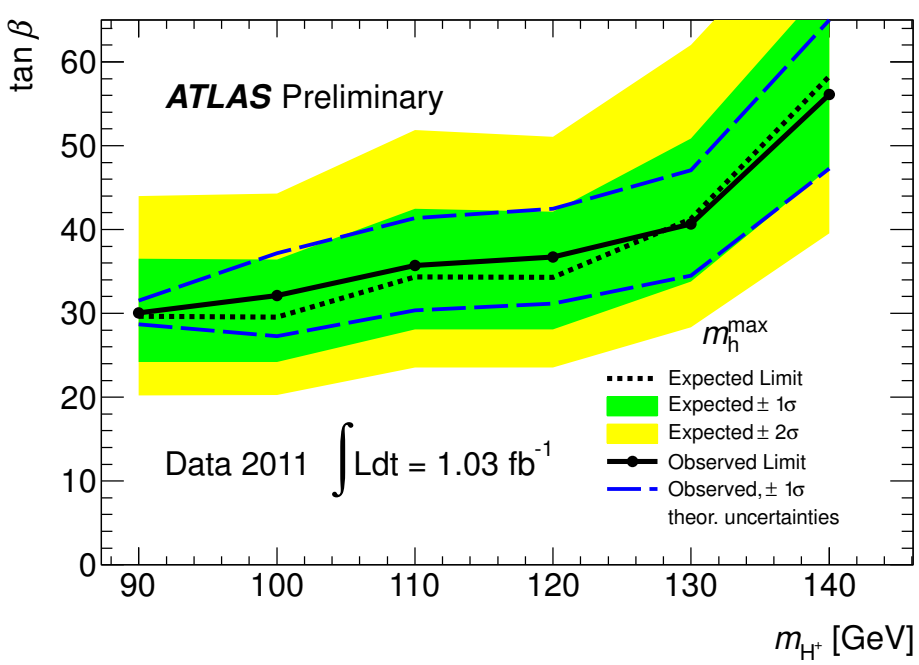
Model independent

- place limit on $BR(t \to H^+b)$ assuming $BR(H^+ \to \tau\nu) = 1$
- can be compared to any model!



MSSM Interpretation

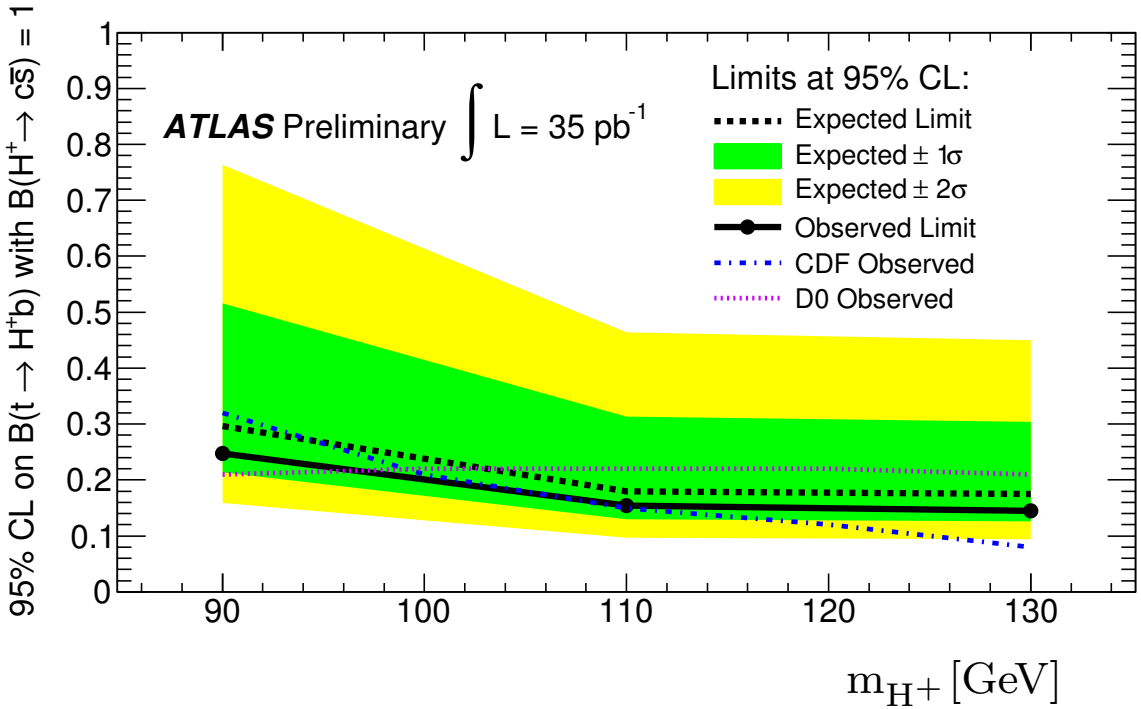
- assume specific (c)MSSM model, here: m_h^{max}
- limit in $(m_{H^+}, \tan\beta)$-plane



$H^+ \to c\bar{s}$, ATLAS-CONF-2011-094, $\int Ldt = 35\,\mathrm{pb}^{-1}$

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

- $H^+ \to c\bar{s}$ dominates for $\tan\beta < 1$
- details of analysis in backup
- observation compatible with background expectation
- set limits on $BR(t \to H^+ b)$ assuming $BR(H^+ \to c\bar{s}) = 1$

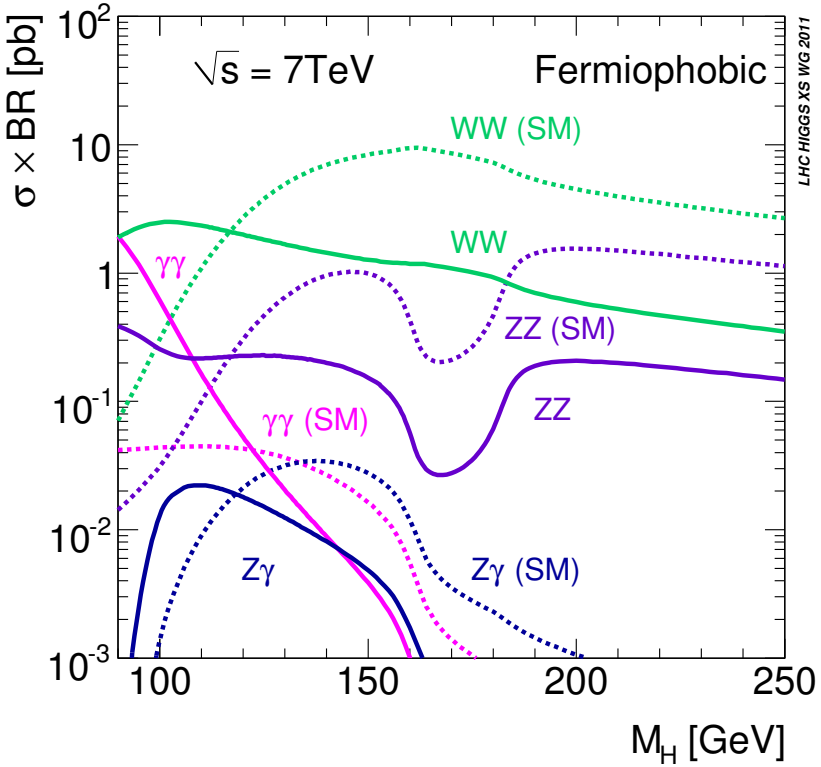


- already with $35\,\mathrm{pb}^{-1}$ comparable to Tevatron results

Fermiophobic $H \to \gamma\gamma$, ATLAS-CONF-2011-149, $\int Ldt = 1.08\,\mathrm{fb}^{-1}$

Fermiophobic Benchmark Scenario

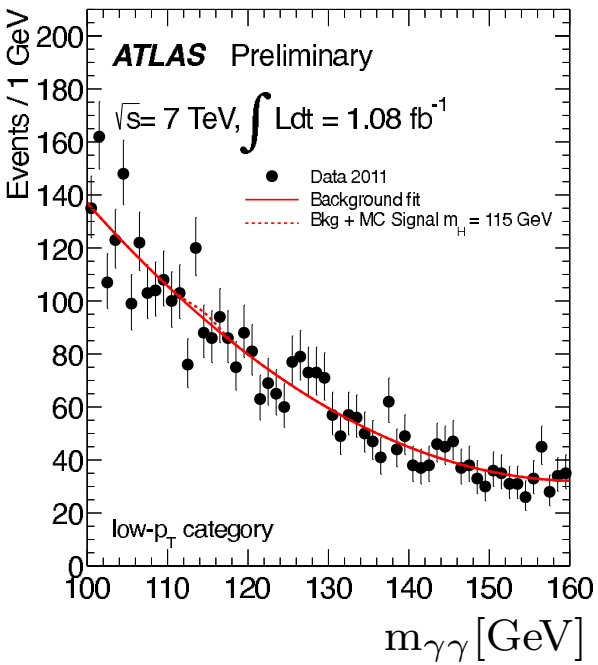
- Higgs doublet or triplet models with decreased couplings to some or all fermions
- fermiophobic benchmark scenario:
  - no coupling to fermions
  - gauge boson couplings as in SM
- $m_H < 120$ GeV:
  $\sigma \times BR(H \to \gamma\gamma)$ increased compared to SM

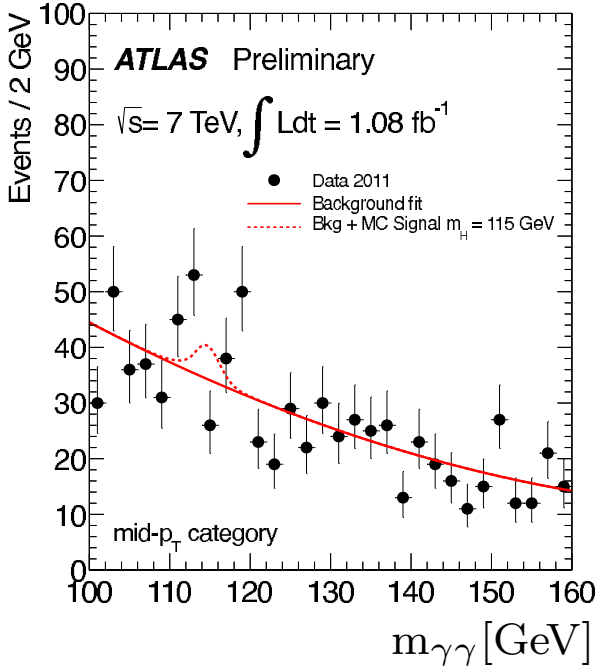


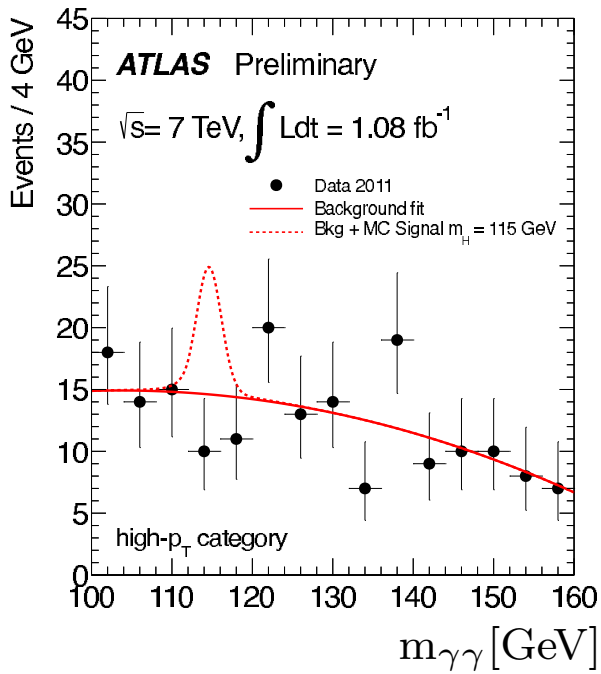
- 2 isolated photons,
  $p_{\mathrm{T}} > 40/20$ GeV,
  $100\ \mathrm{GeV} < m_{\gamma\gamma} < 160\ \mathrm{GeV}$
- VH and VBF only $\Rightarrow$ boosted Higgs, use 3 bins of $p_{\mathrm{T}}(\gamma\gamma)$:
  - $p_{\mathrm{T}}(\gamma\gamma) \leq 50$ GeV
  - $50\ \mathrm{GeV} < p_{\mathrm{T}}(\gamma\gamma) \leq 100$ GeV
  - $100\ \mathrm{GeV} < p_{\mathrm{T}}(\gamma\gamma)$

m_H [GeV]	$\sigma \times BR$ [fb]	Number of expected events	Fraction of events		
			low-p_{T}	mid-p_{T}	high-p_{T}
110	163.4	60.3	0.32	0.38	0.30
115	90.4	35.0	0.32	0.38	0.30
120	52.8	21.1	0.32	0.37	0.31
125	20.5	13.3	0.29	0.39	0.32
130	3.9	8.9	0.29	0.38	0.33
Events in data		5063	4073	805	185

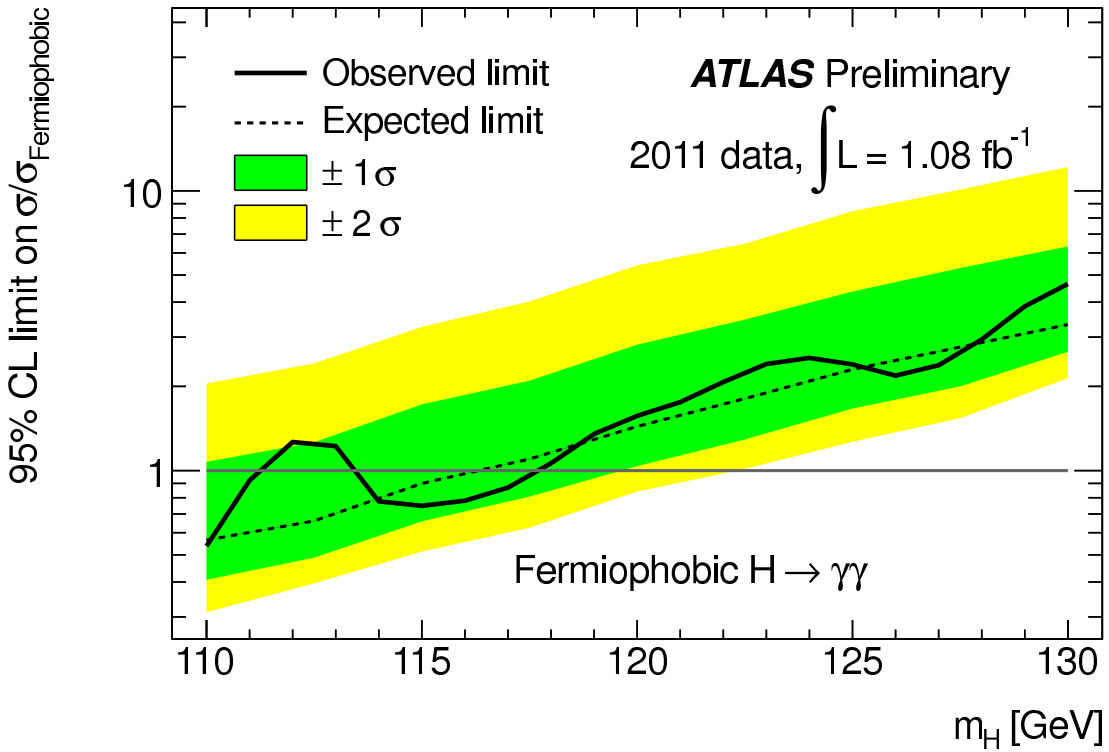
- background: 2^{nd} order Bernstein polynomial
- signal: Crystal Ball + wide Gaussian







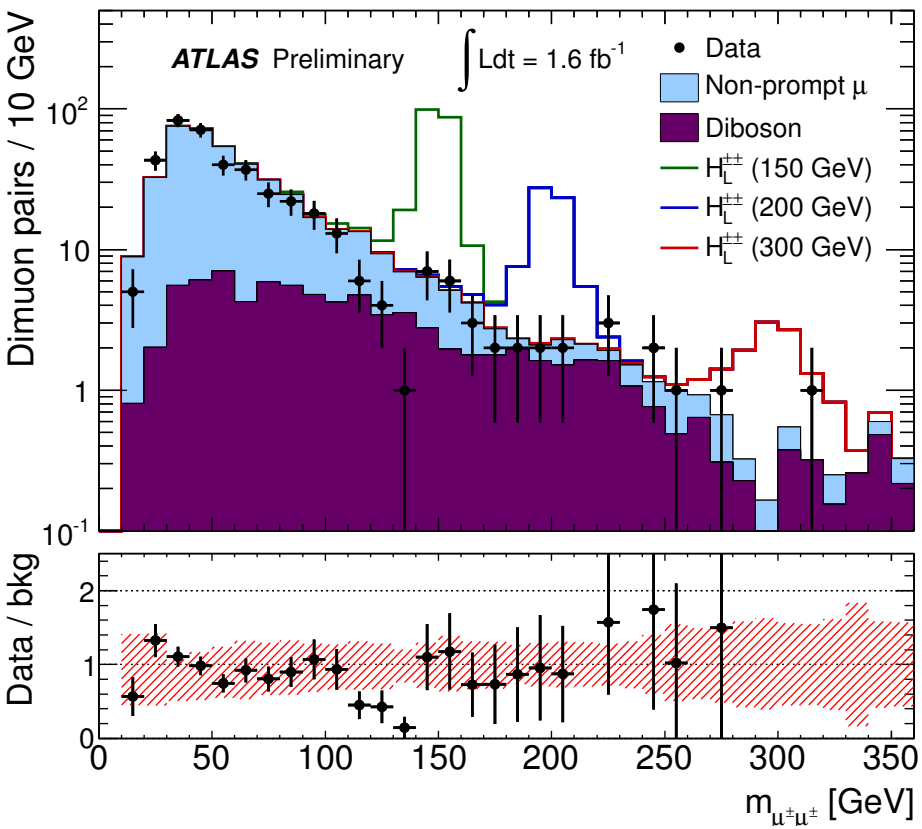
Exclusion limits @95% CL



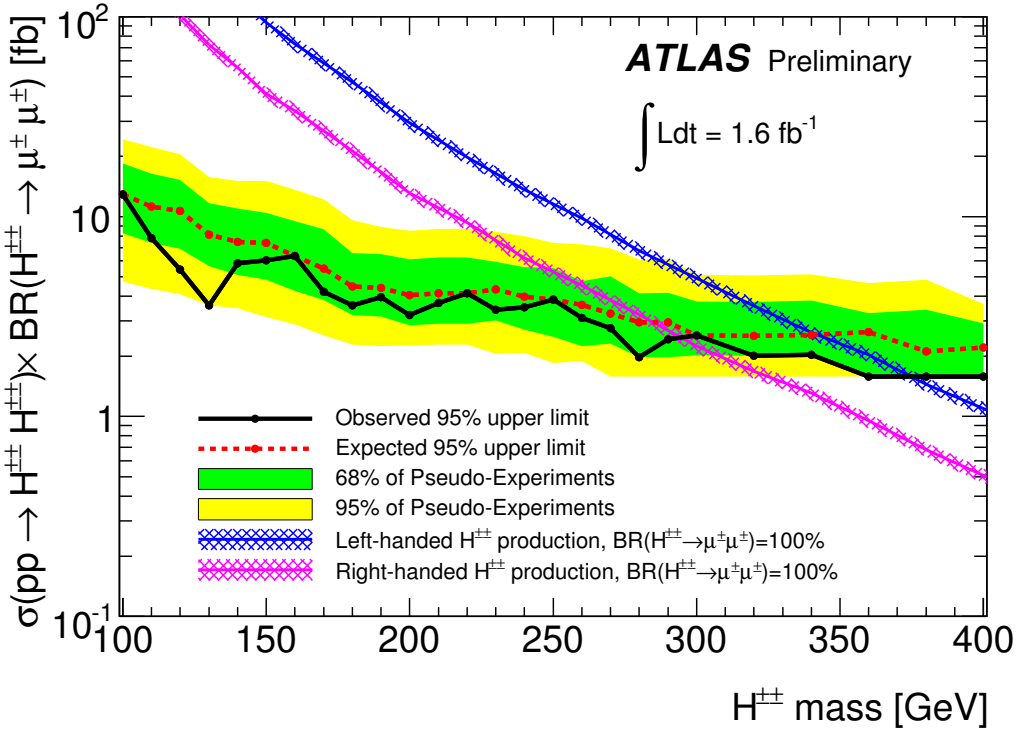
- simplistic fermiophobic benchmark model
- expected:
  110 GeV — 116 GeV
- observed:
  110 GeV — 111 GeV and 113.5 GeV — 117.5 GeV

Doubly charged Higgs, ATLAS-CONF-2011-127, $\int Ldt = 1.6\,\mathrm{fb}^{-1}$

- predicted in left-right symmetric, Higgs triplet and little Higgs models
- production via $pp \to H^{++}H^{--}$
- same-sign dimuons
- look for dimuon mass resonance



- no excess ⇒ set limits on $\sigma(H^{++}H^{--}) \times BR(H^{\pm\pm} \to \mu^{\pm}\mu^{\pm})$



- $m_{H_L^{++}} < 375$ GeV, $m_{H_R^{++}} < 295$ GeV
  (assuming $BR(H^{\pm\pm} \to \mu^{\pm}\mu^{\pm}) = 1$)

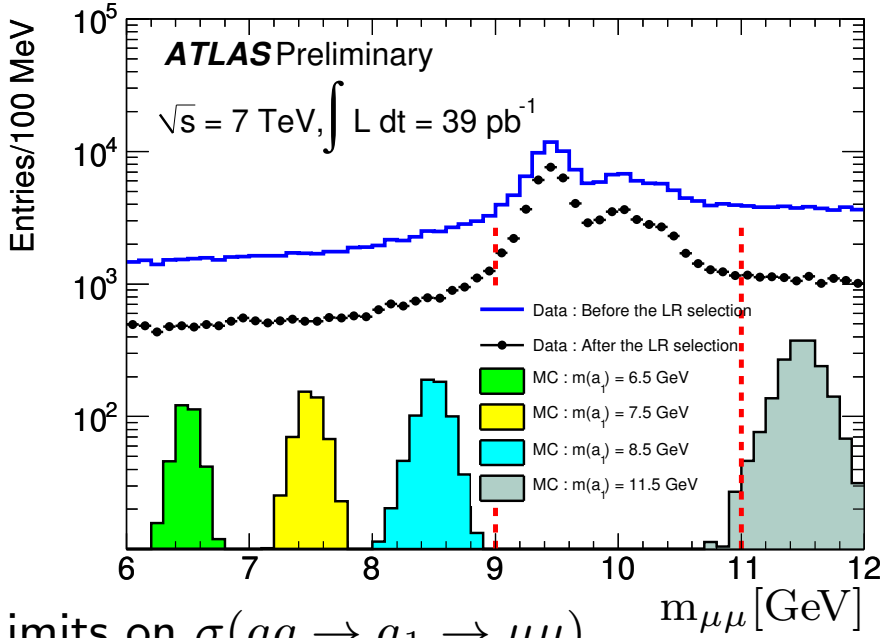
NMSSM $a_1 \to \mu\mu$, ATLAS-CONF-2011-020, $\int Ldt = 39\,\mathrm{pb}^{-1}$

- NMSSM: additional complex singlet scalar field to solve μ problem
- 3 CP-even scalars (h_1, h_2, h_3), 2 CP-odd scalars (a_1, a_2), $H^{\pm}$
- a_1 can be very light, i.e. $m_{a_1} < 2m_B$

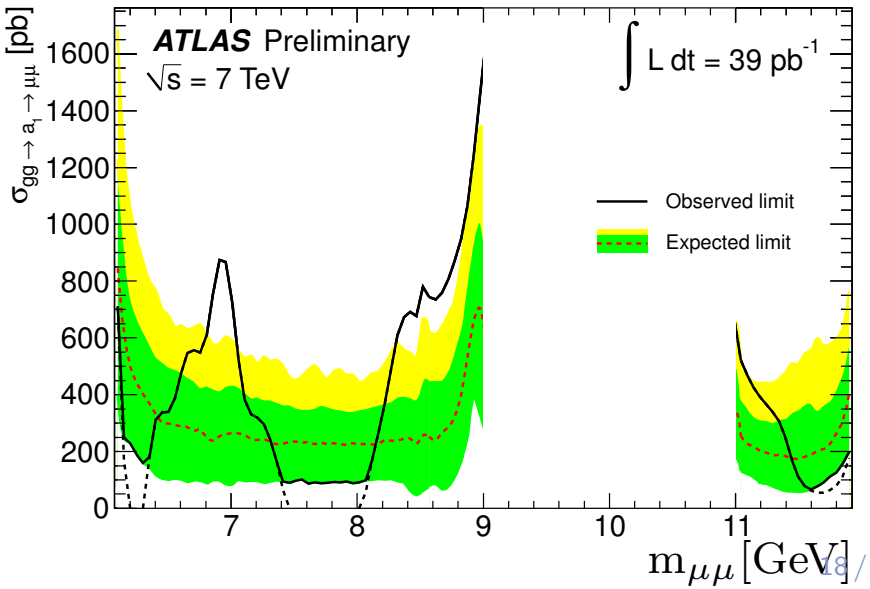
Analysis

- opposite sign dimuons
- likelihood ratio selection
- limit setting by fit to mass spectrum
- Υ region excluded

Invariant dimuon mass:

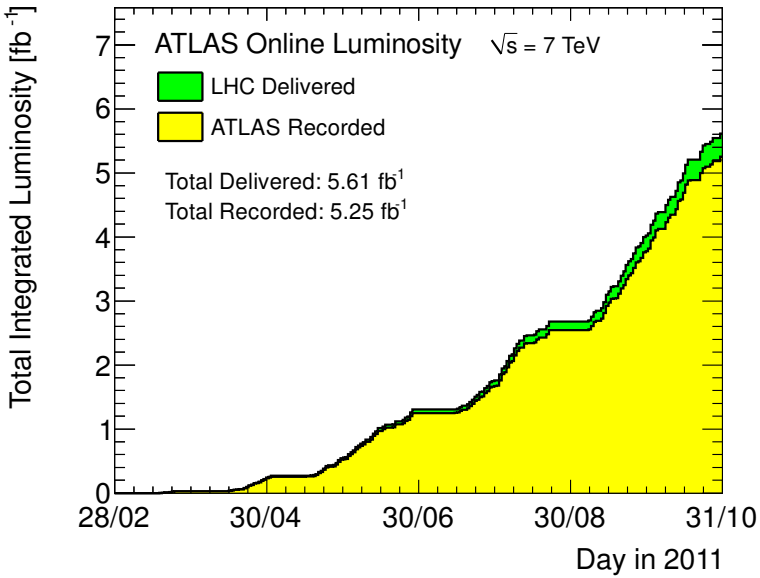


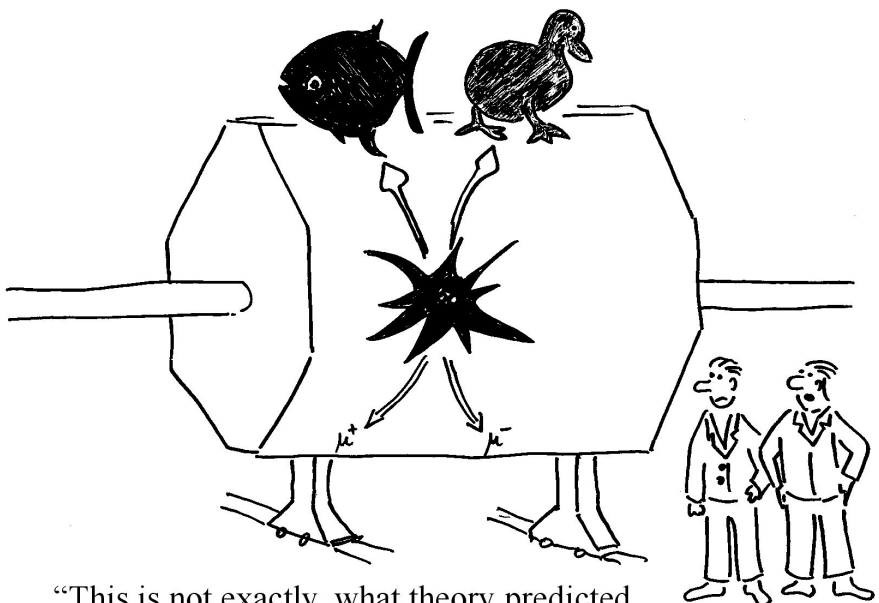
Limits on $\sigma(gg \to a_1 \to \mu\mu)$



Summary and Outlook

- wide variety of BSM Higgs models probed
- observations compatible with Standard Model expectations
- set strict upper limits on cross sections and branching fractions
- more data being analyzed, updates soon
- still large parts of BSM Higgs models open for discovery!





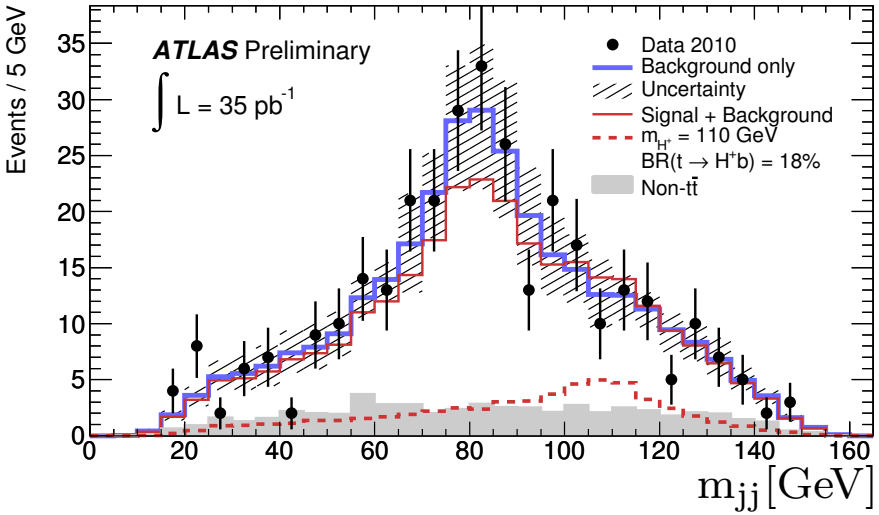
"This is not exactly, what theory predicted for the Higgs decay!"

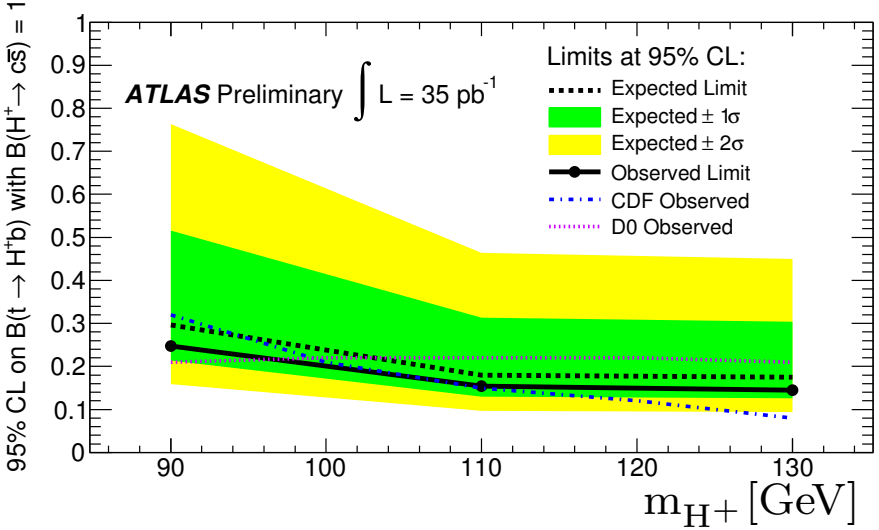
Backup

$H^+ \to c\bar{s}$, ATLAS-CONF-2011-094, $\int Ldt = 35\,\mathrm{pb}^{-1}$

$H^+ \to c\bar{s}, W \to e\nu/\mu\nu$

- $H^+ \to c\bar{s}$ dominates for $\tan\beta < 1$
- suppress QCD multijet background by requiring large $E_{\mathrm{T}}^{\mathrm{miss}}$ and m_T
- kinematic fit with top mass constraint to select best charged Higgs candidate
- remaining QCD background estimated data-driven
- $W+ \geq 4$ jets normalized to data
- set limits on $BR(t \to H^+b)$ assuming $BR(H^+ \to c\bar{s}) = 1$





- already with $35\,\mathrm{pb}^{-1}$ comparable to Tevatron results

Experimental techniques: $\tau\tau$ mass reconstruction

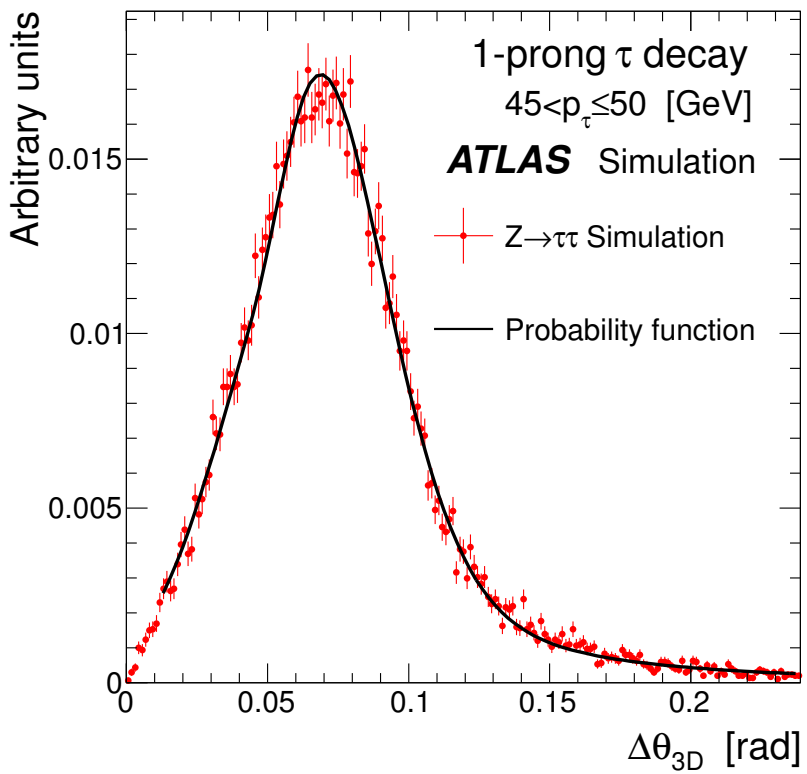
- use mass sensitive variable as final discriminant
  - $e\mu$ channel: effective mass

$$m_{\tau\tau}^{\mathrm{eff.}} = \sqrt{(p_e + p_\mu + p_{E_{\mathrm{T}}^{\mathrm{miss}}})^2}, \qquad p_{E_{\mathrm{T}}^{\mathrm{miss}}} = (E_{\mathrm{T}}^{\mathrm{miss}}, E_{\mathrm{T}}^{\mathrm{miss},x}, E_{\mathrm{T}}^{\mathrm{miss},y}, 0)$$

  - $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ channel: visible mass $m_{\tau_{\mathrm{had}}\tau_{\mathrm{had}}}$

Missing Mass Calculator (MMC)

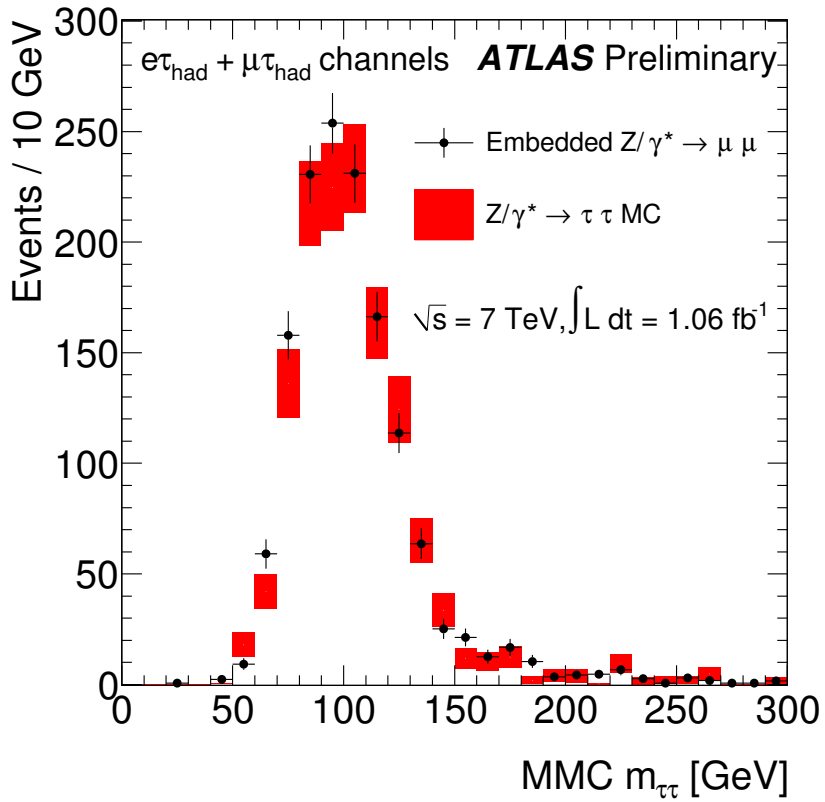
- used in $e/\mu\tau_{\mathrm{had}}$ channel
- NIM A654 (2011) 481
- split $E_{\mathrm{T}}^{\mathrm{miss}}$ in two vectors ($\equiv$ neutrinos from each τ)
- invariant mass with visible decay products $= m_\tau$
- scan over free pars. and weight with PDF to come from τ decay
- find mass with highest probability



Experimental techniques: Embedding

$Z \to \tau\tau$ background estimation

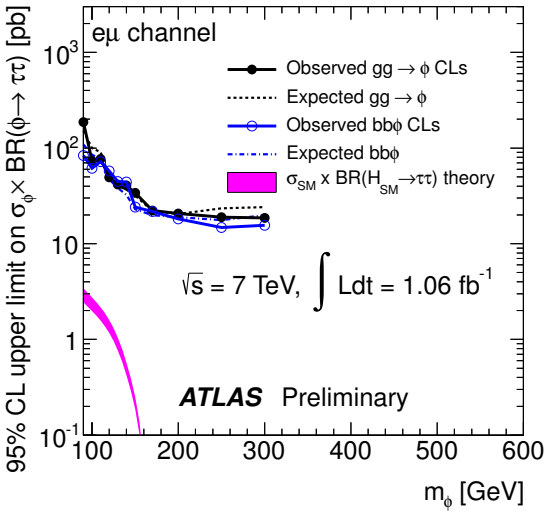
- select $Z \to \mu\mu$
- remove $\mu's$, take these as τ's
- simulate τ-decays and detector response
- remerge with original event
- underlying event, pileup, hadronic activity: taken from real data!



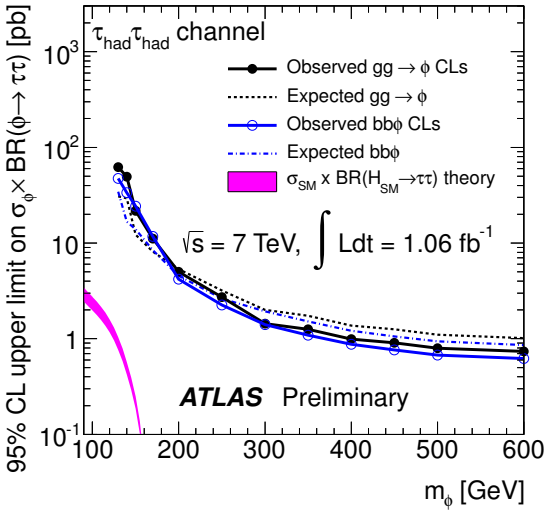
MSSM neutral $h/H/A \to \tau\tau$: Limits on $\sigma \times BR(\phi \to \tau\tau)$

- assume 100% gluon-gluon-fusion or 100% b-associated production (acceptances slightly different)
- assume only one resonance
- can place model-independent limits on $\sigma \times BR$

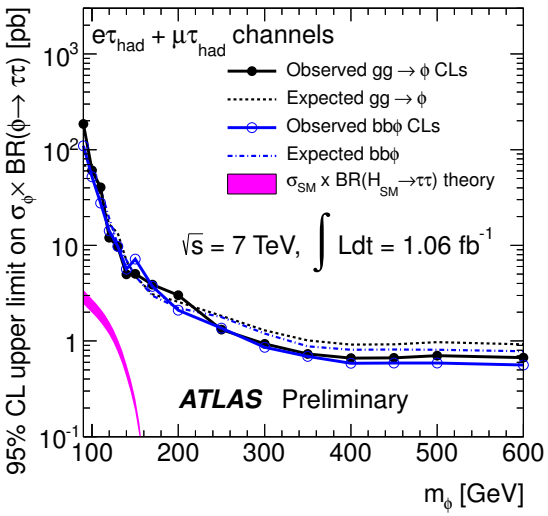
$e\mu$ only



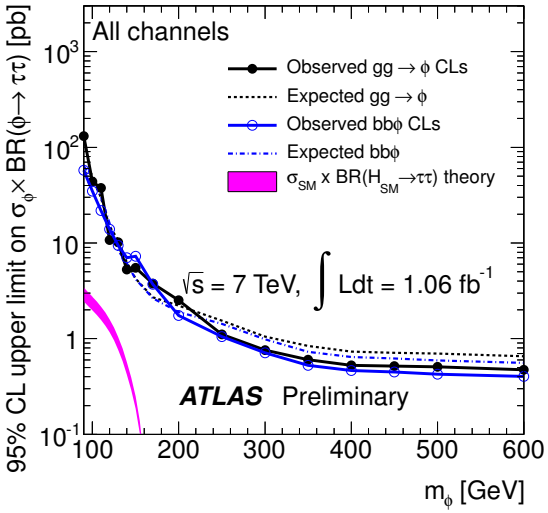
$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ only



$\ell\tau_{\mathrm{had}}$ only

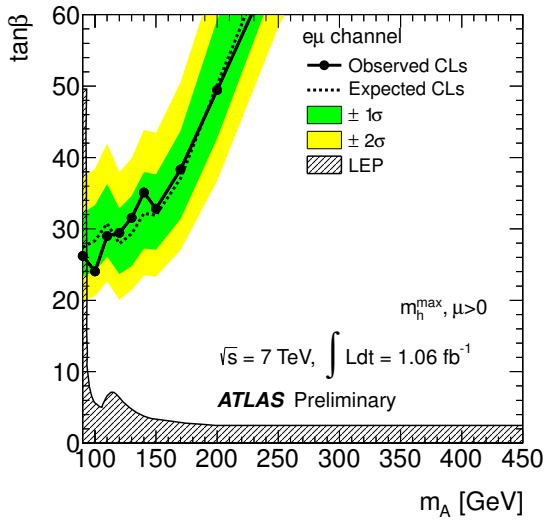


combination

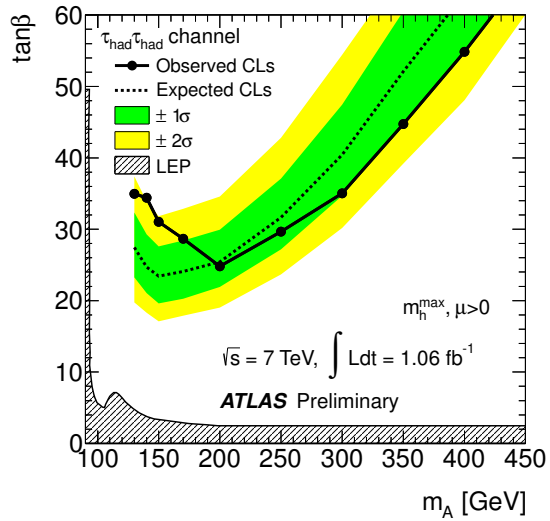


MSSM neutral $h/H/A \to \tau\tau$: Limits in $(m_A, \tan\beta)$-plane

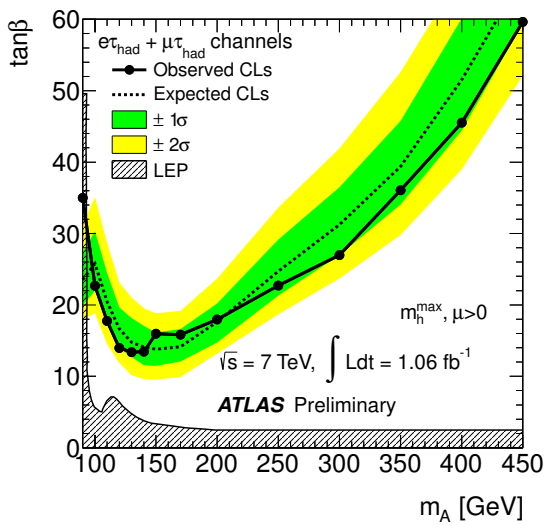
$e\mu$ only



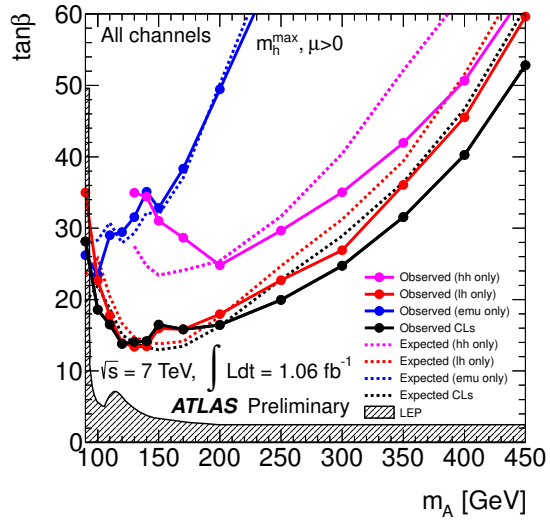
$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ only



$\ell\tau_{\mathrm{had}}$ only

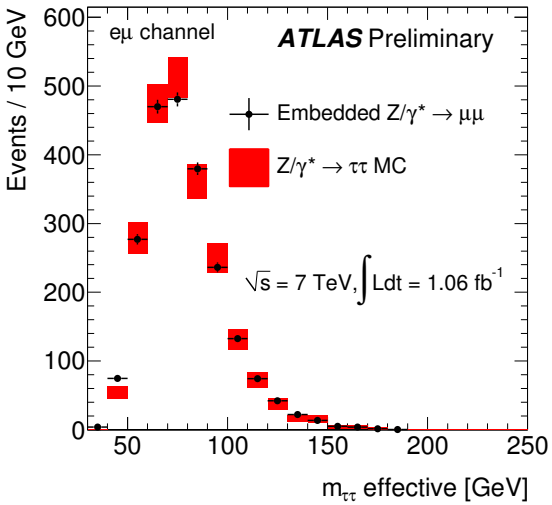


combination

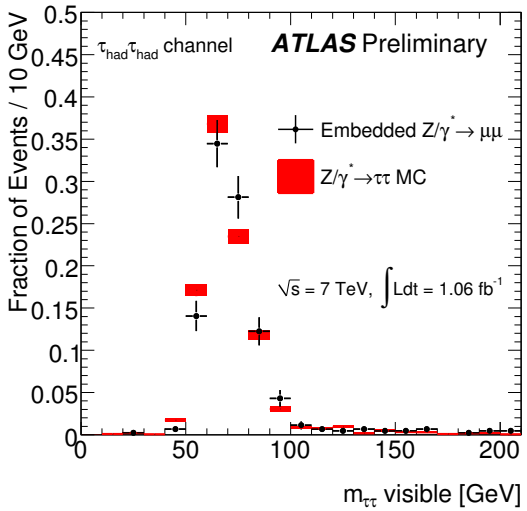


MSSM neutral $h/H/A \to \tau\tau$: Additional Plots

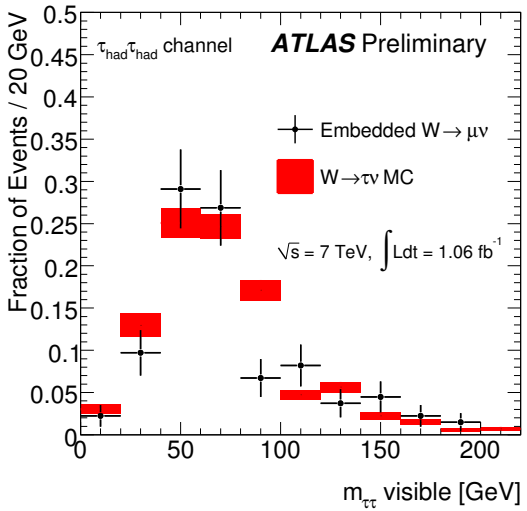
$e\mu$ embedding



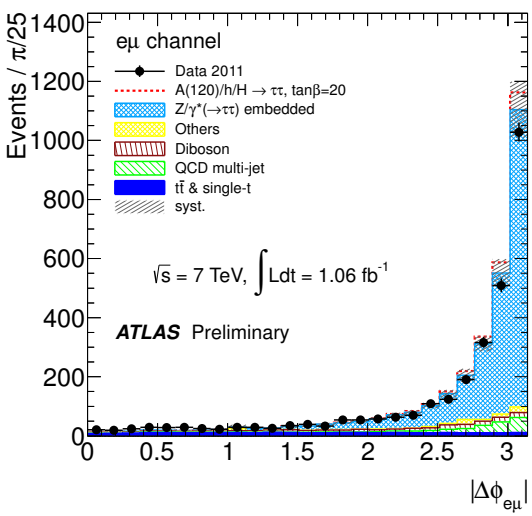
$\tau_{\text{had}}\tau_{\text{had}}$ embedding



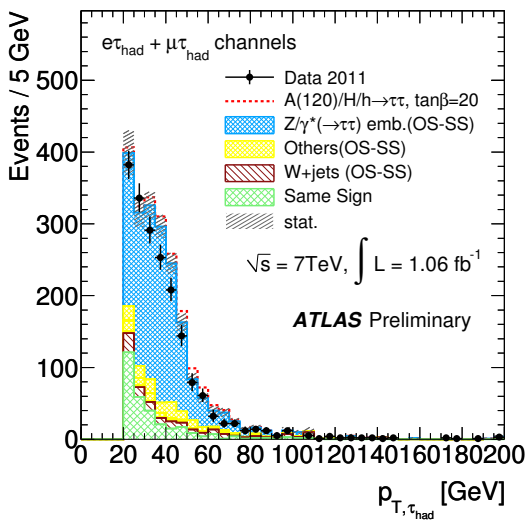
$\tau_{\text{had}}\tau_{\text{had}}$ embedding



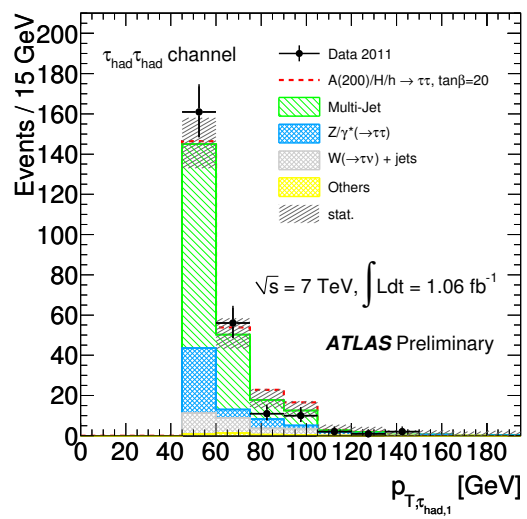
$e\mu$: $\Delta\phi_{e\mu}$



$\ell\tau_{\text{had}}$: p_{T}^{τ}

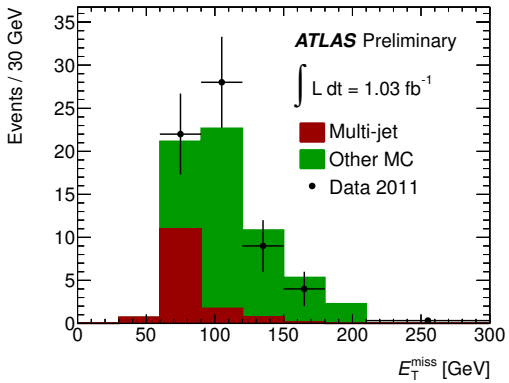


$\tau_{\text{had}}\tau_{\text{had}}$: p_{T}^{τ}

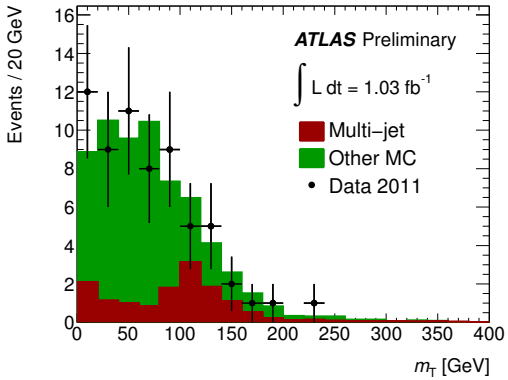


$H^+ \to \tau_{\mathrm{had}}\nu$: Additional Plots

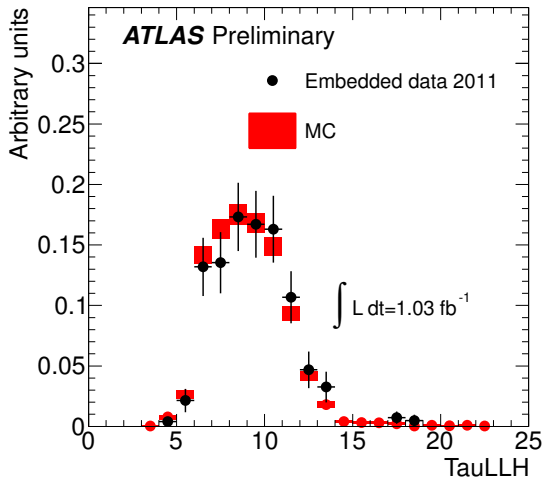
Multi-jet: fit to $E_{\mathrm{T}}^{\mathrm{miss}}$



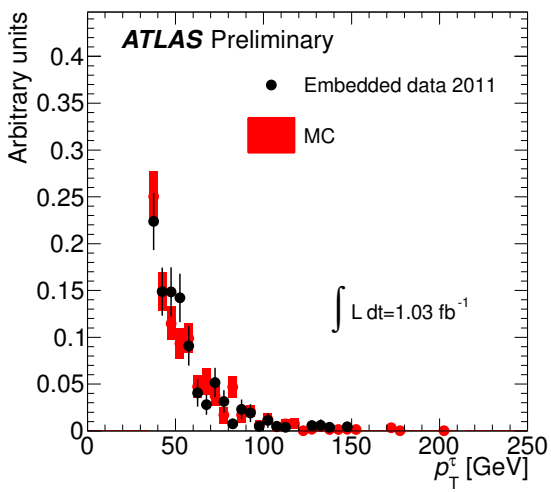
Multi-jet: m_T



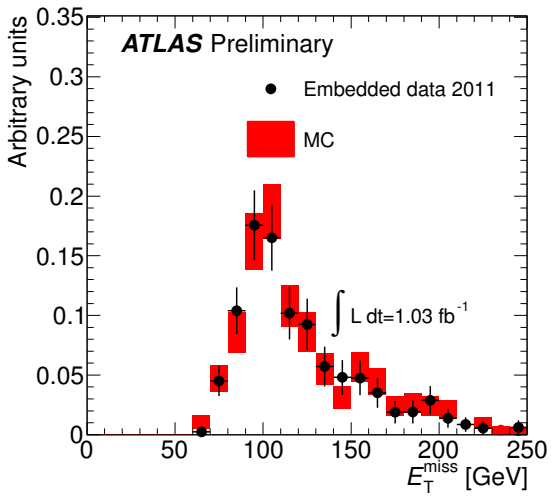
Embedding: τ-Likelihood



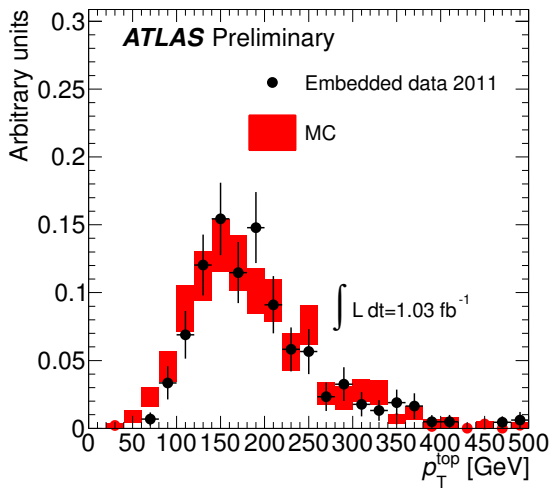
Embedding: p_{T}^{τ}



Embedding: $E_{\mathrm{T}}^{\mathrm{miss}}$

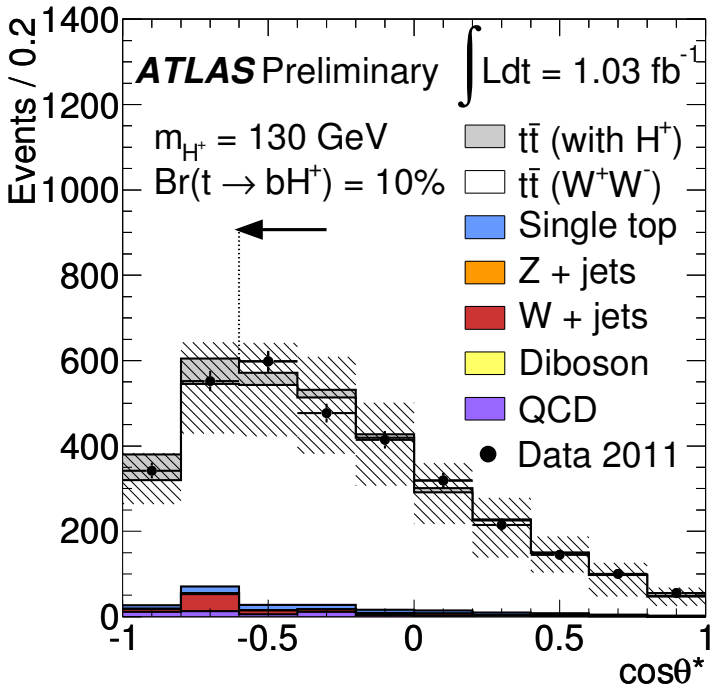


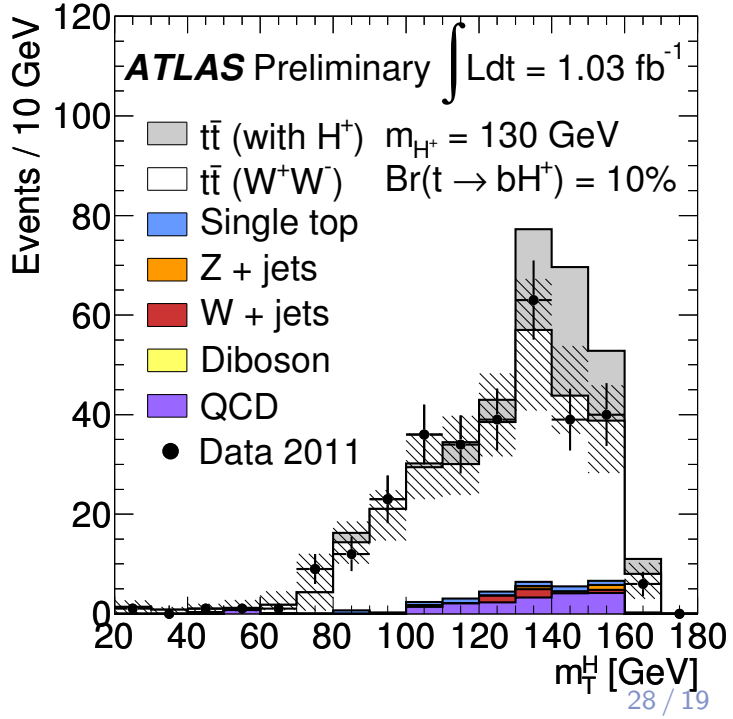
Embedding: p_{T}^{top}



1 lepton channel ($H^+ \to \tau_{\mathrm{lep}}\nu, W \to q\bar{q}'$)

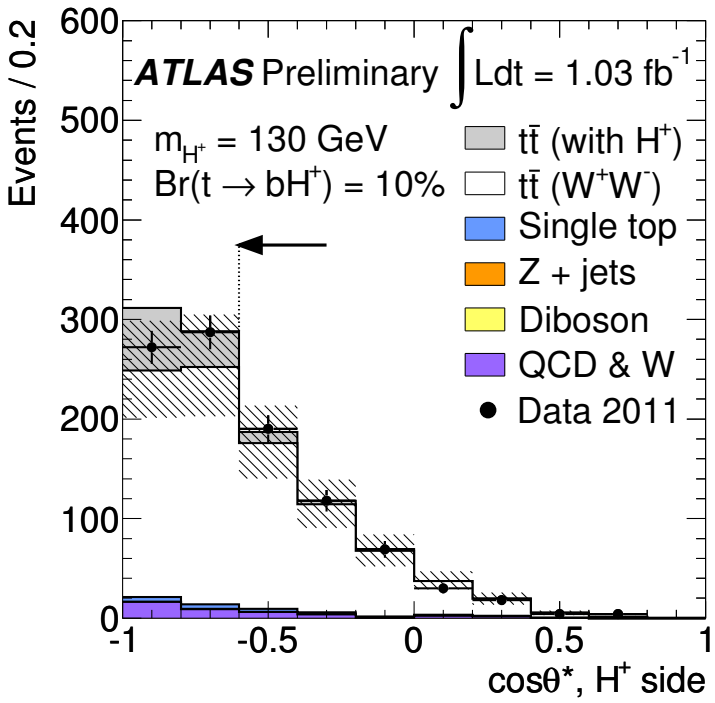
- exactly one electron or muon
- ≥ 4 jets, exactly two b-tagged, high $E_{\mathrm{T}}^{\mathrm{miss}}$
- combinatorics:
  $\min\left(\chi^2 = \frac{(m_{jjb}-m_{\mathrm{top}})^2}{\sigma_{\mathrm{top}}^2} + \frac{(m_{jj}-m_W)^2}{\sigma_W^2}\right) < 5$
- cannot rely on theory prediction of $\sigma_{t\bar{t}\to b\bar{b}W^+W^-}$
  - $\cos\theta_l^* = \frac{2m_{bl}^2}{m_{\mathrm{top}}^2 - m_W^2} - 1$
  - constrain $t\bar{t} \to b\bar{b}W^+W^-$ contribution (cannot rely on theory) from control region: $\cos\theta_l^* > -0.2$
  - signal region: $\cos\theta_l^* < -0.6$, $m_T^W < 60$ GeV
- final discriminant: transverse mass m_T^H
  (Phys. Rev. D 81 (2010) 055010)
- QCD background:
  data-driven estimate (fake rates method)

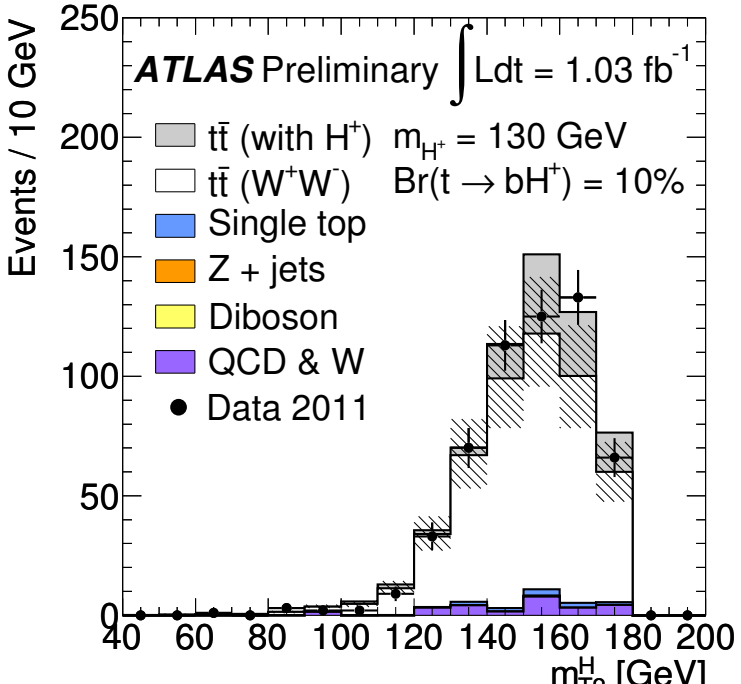




2 lepton channel ($H^+ \to \tau_{\mathrm{lep}}\nu, W \to \ell\nu$)

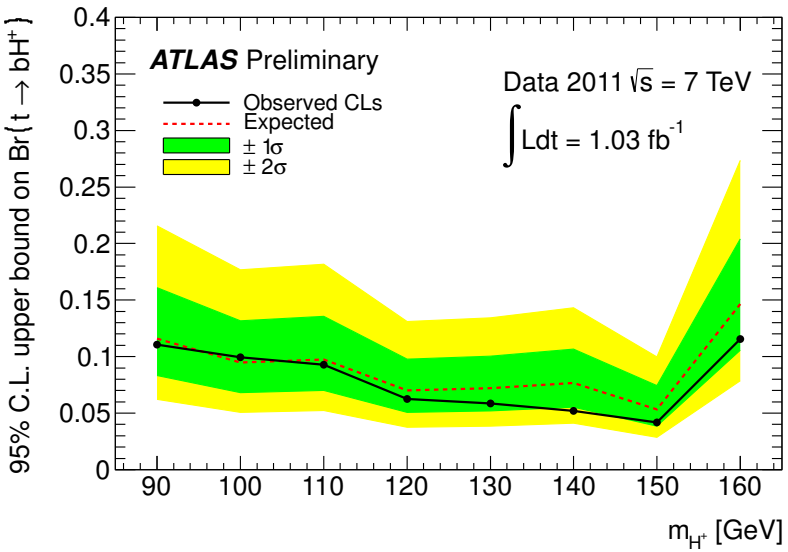
- two oppositely charged leptons
- ≥ 2 jets, exactly two b-tagged
- ee and $\mu\mu$: Z-veto, $E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV
- $e\mu$: $p_{\mathrm{T}}^{\mu} + p_{\mathrm{T}}^{e} + \sum E_{\mathrm{T}}^{\mathrm{jets}} > 130$ GeV
- cannot rely on theory prediction of $\sigma_{t\bar{t}\to b\bar{b}W^+W^-}$
  - constrain $t\bar{t} \to b\bar{b}W^+W^-$ contribution from control region:
    $\cos\theta_l^* > -0.4$
  - Signal region:
    $\cos\theta_l^* < -0.6$
- final discriminant: generalised transverse mass m_{T2}^H (Phys. Rev. D 81 (2010) 055010)
- QCD and W background: data-driven estimate (fake rates method)



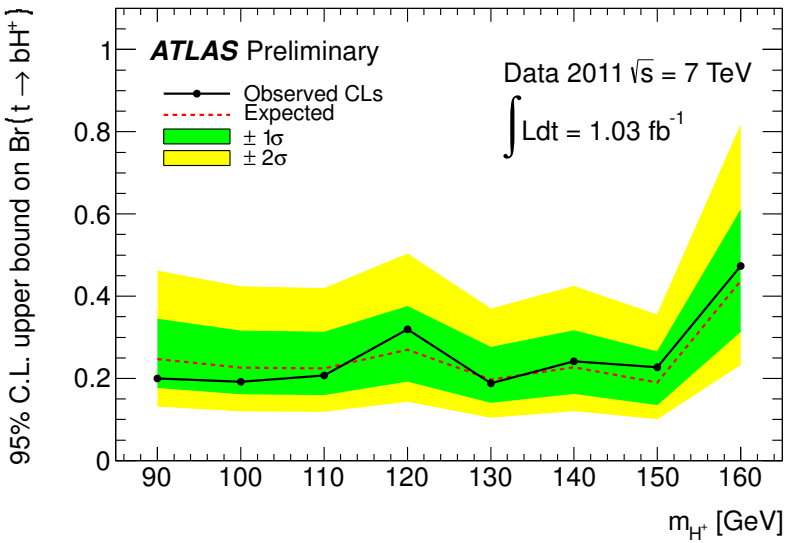


$H^+ \to \tau_{lep}\nu$: Additional Plots

Limit for 1 lepton alone



Limit for 2 lepton alone



$a_1 \to \mu\mu$: Additional Plots

Background-only fits