Search for $H^{\pm\pm}$ and $H^{\pm}$ to other states than $\tau_{had} + \nu$ in ATLAS

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On behalf of the ATLAS Collaboration

cH±arged 2012
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Prospects for Charged Higgs Discovery at Colliders

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Outline

- Introduction
- Charged Higgs analyses
  - $H^{\pm} \rightarrow \tau_{lep}$ + lepton
  - $H^{\pm} \rightarrow \tau_{lep}$ + jets
  - $H^{\pm} \rightarrow c\bar{s}$
- Doubly charged Higgs
  - Search for anomalous production of prompt like-sign muon pairs

$H^{\pm}$ analyses

Introduction (1): Theory

- Standard Model:
  - Standard Model (SM) very successful theory in describing fundamental particles and their interactions
  - Important to understand mechanism by which electroweak symmetry breaking (EWSB) occurs
  - In SM: single complex scalar doublet field
    → massive electroweak gauge bosons and a scalar particle (Higgs boson)
  - This year discovery of “SM-Higgs-like” boson by ATLAS and CMS

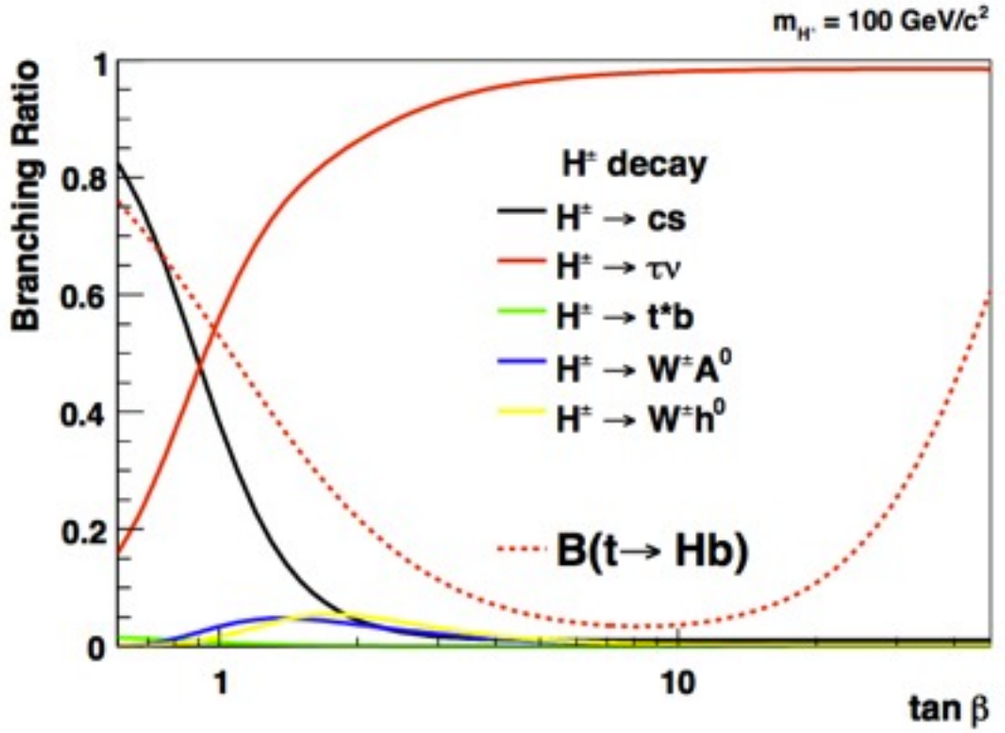
- Beyond the Standard Model:
  - many models propose extension of Higgs sector to explain EWSB
  - simple model: Two Higgs-doublet model (2HDM)
    - 5 physical Higgs boson states: 3 neutral, 2 charged
    - discovery of charged Higgs → definite signal of new physics beyond SM

Introduction (2): MSSM

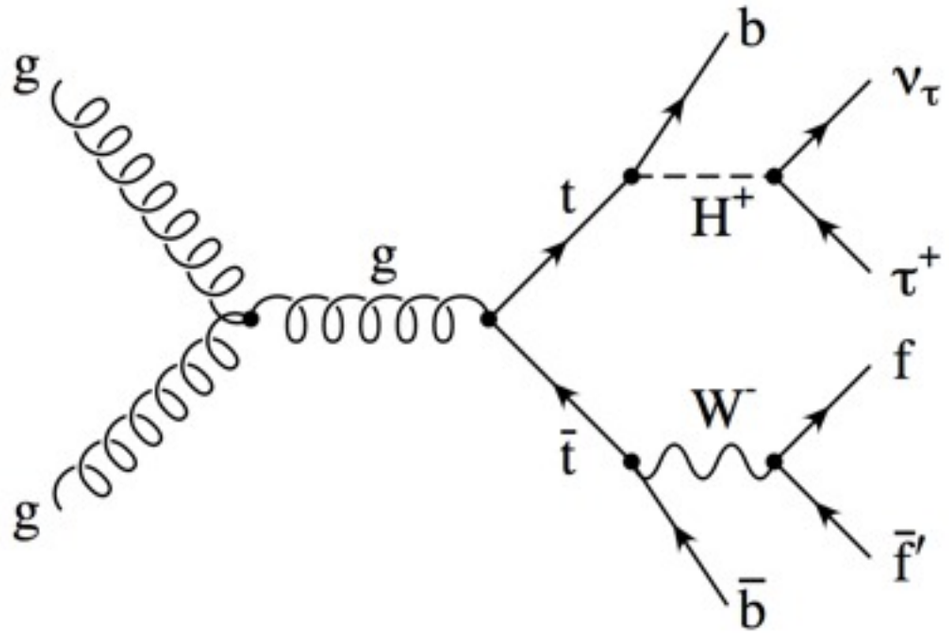
Minimal Supersymmetric Standard Model (MSSM)

- employs type-II 2HDM
- one doublet couples to up-type fermions, other one to down-type fermions
- at tree level, MSSM Higgs sector is determined by only two independent parameters, usually chosen to be:
  - mass of H^+: m_{H+}
  - ratio of the two Higgs doublet vacuum expectation values: tan β

- Decay of charged Higgs boson:
  - light H^+ ($m_{H+}<m_t$) decays primarily to $c\bar{s}$ and $\tau^+\nu$ depending on tan β and m_{H+}
  - heavy H^+ ($m_{H+}>m_t$) decays primarily to $\tau^+\nu$ and $t\bar{b}$
    - not discussed in this talk
- Light charged Higgs boson:
  - for tan β < 1: $H^+ \rightarrow c\bar{s}$ dominates with BR ($H^+ \rightarrow c\bar{s}$) of ~20-40% for m_{H+} ~ 100GeV
  - for tan β > 2: $H^+ \rightarrow \tau^+\nu$ channel dominates with > 90%
    - also remains sizeable for 1 < tan β < 2



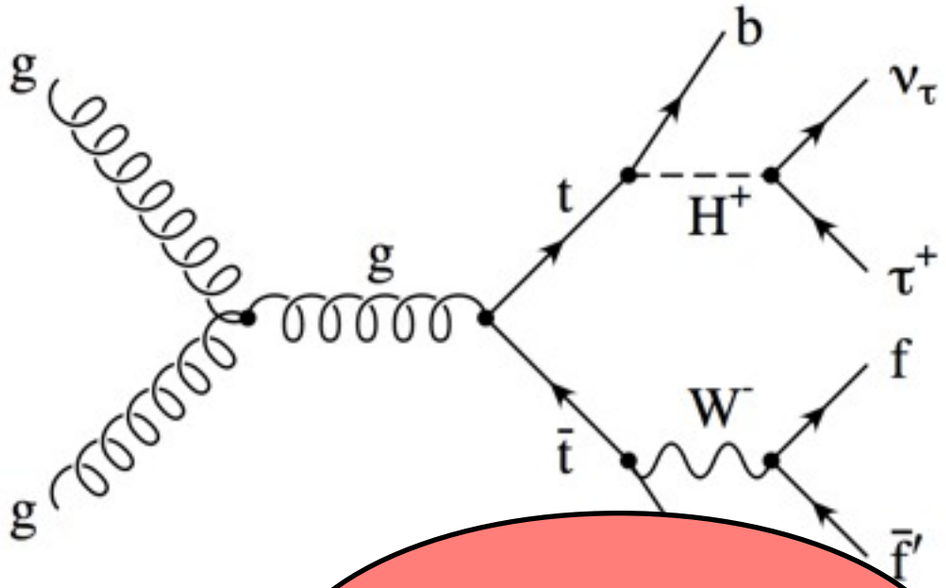
$H^{\pm} \rightarrow \tau\nu$ channels



- Complex final state:
  - reconstruction of final state challenging with τ lepton, missing energy from ν_τ, 2 b-jets and lepton + ν_ℓ or jets depending on W decay
  - decay channels are classified by decays of τ lepton and W boson

$\bar{t}t \rightarrow b\bar{b}\, WH^+$	τ decays to e or μ	τ decays hadronically
W decays leptonically: f = e/μ	τ_{lep} + lepton	τ_{had} + lepton
W decays hadronically (into two jets): f = q	τ_{lep} + jets	τ_{had} + jets

$H^{\pm} \rightarrow \tau\nu$ channels



- Complex final state:
  - reconstruction of final state challenging with τ lepton, missing energy from ν_τ, 2 b-jets and lepton + ν_ℓ or jets depending on W decay
  - decay channels are cl… of τ lepton and W b…

See Patrick's talk!

Covered in this talk

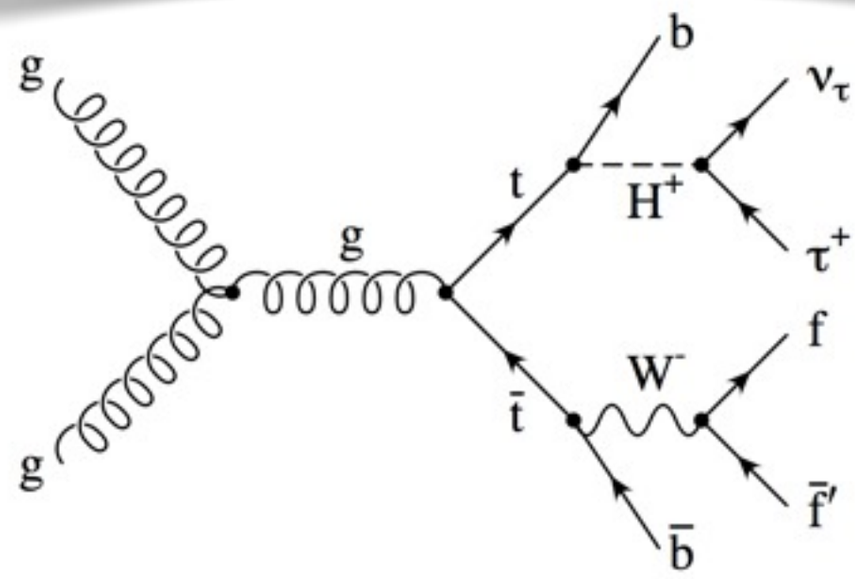
	τ decays to e or μ	τ decays hadronically
W decays leptonically: f = e/μ	τ_{lep} + lepton	τ_{had} + lepton
W decays hadronically (into two jets): f = q	τ_{lep} + jets	τ_{had} + jets

$H^{\pm} \rightarrow \tau_{lep}\nu$ + lepton analysis

ATLAS-CONF-2011-151

Event Selection

Charged Higgs boson search in di-lepton channel with integrated luminosity of 1.03 fb^{-1} and $\sqrt{s}$ = 7 TeV



- Cut-based selection
  - two oppositely charged leptons, one matched to the single lepton trigger (electron threshold 20 GeV, muon threshold 18 GeV)
  - at least two jets, including two b-tagged jets
  - for ee and μμ events:
    - $m_{\ell\ell} > 15$ GeV
    - $|m_{\ell\ell}-m_Z| > 10$ GeV (Z veto)
    - $E_T^{miss} > 40$ GeV
  - for eμ events: scalar ∑ of the transverse energies of the two leptons and all selected jets must satisfy $\sum E_T > 130$ GeV

- Four-fold ambiguity in assigning leptons and b-jets to parents
  - First: select events where two ℓ-b combinations with cos $\Theta_\ell^* < 1$ and which minimise $\Delta R(\ell,b)_{pair1}+\Delta R(\ell,b)_{pair2}$
    - efficiency in simulated $\overline{tt}$ events is 66%
  - then assign particles of the ℓ-b pair with smallest cos Θ_ℓ^* value to the "H^+ side" and the particles of the other pair to the "W side"
    - efficiency of 62% in simulated events with $m_{H+} = 130$ GeV

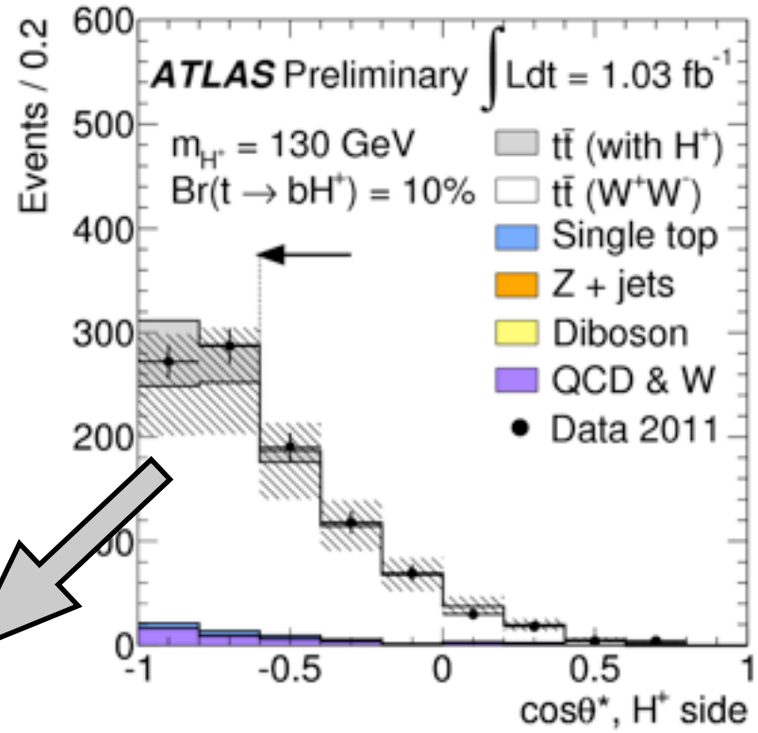
Discriminating Variables

Identification of discriminating variables allowing a distinction between leptons produced in $\tau \rightarrow \ell\nu_\ell\nu_\tau$ decays and leptons from W boson decays

- invariant mass $m_{b\ell}$ of b-quark and lepton ℓ from the same top quark → expressed as

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

$\cos\Theta_\ell^* \sim -1$ for H^+ side: minimised due to smaller momentum of b-quark (if $m_{H+} > m_W$) and smaller momentum of ℓ from τ

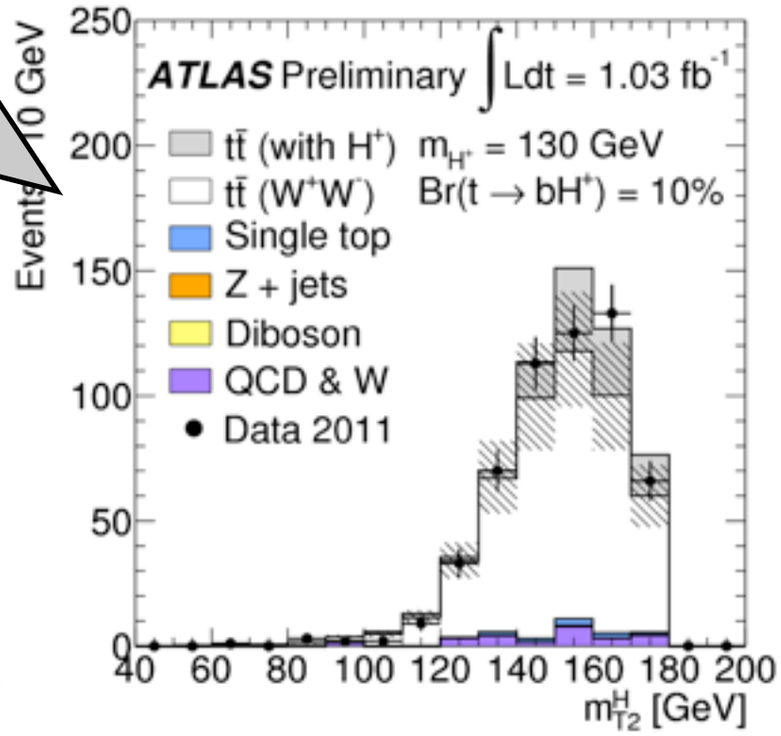


signal region: $\cos\Theta_\ell^* < -0.6$

→ for events on the "H^+ side" in the signal region the generalised transverse mass m^H_{T2} is used as discriminating variable to search for H^+

- generalised transverse mass: maximised charged Higgs boson mass of kinematic system

$$m_{\text{T2}}^H = \max_{\{constraints\}} [m_{\text{T}}^H(\vec{p}_{\text{T}}^{\,H^+})]$$

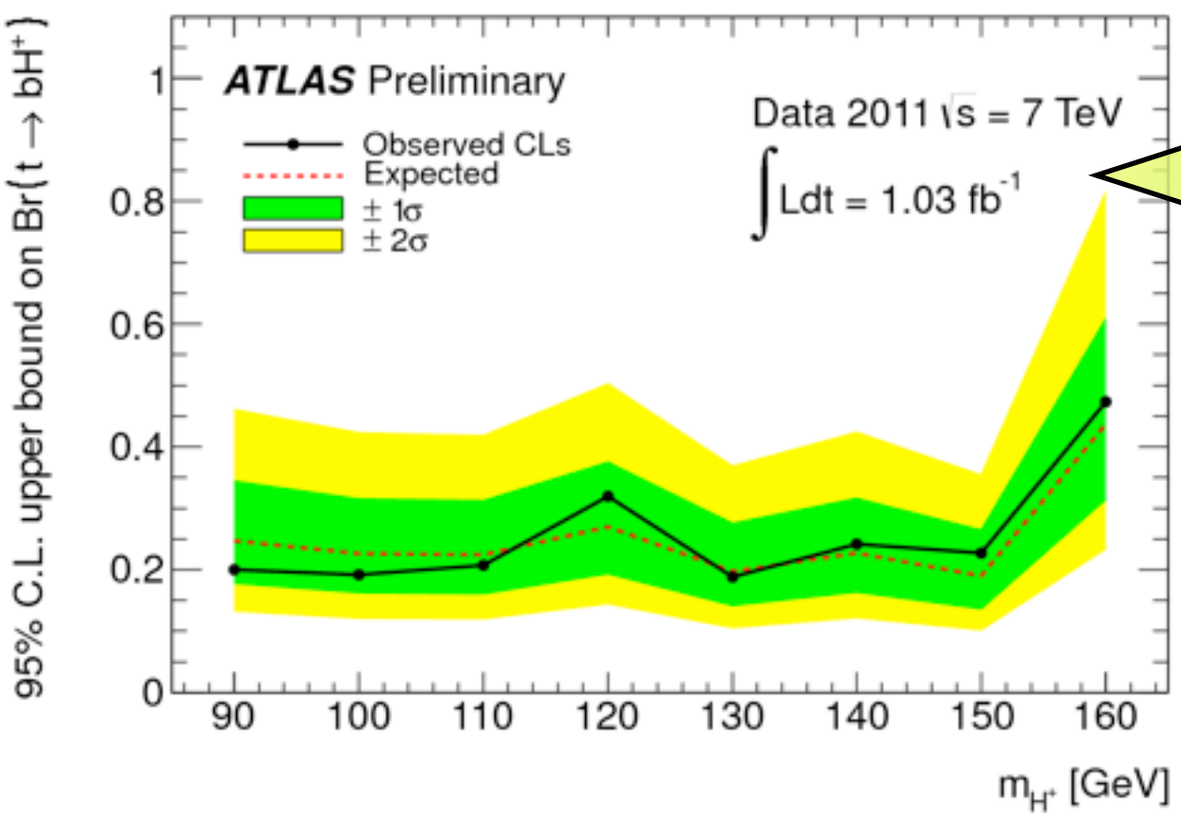


Neither an excess of events nor a significant deformation of mass distribution is observed

Results

Data agree well with SM expectation, assuming BR($H^+ \to \tau\nu$) = 1
→ upper limits on BR($t \to bH^+$) as a function of the charged Higgs boson mass

m_{H^+} (GeV)	90	100	110	120	130	140	150	160
95% C.L. observed (expected) limit on $\mathcal{B}(t \to bH^+)$ for the dilepton channel	20.0% (24.7%)	19.2% (22.6%)	20.7% (22.4%)	32.0% (26.9%)	18.8% (19.8%)	24.2% (22.6%)	22.7% (19.0%)	47.3% (43.7%)



Expected and observed 95% CL exclusion limits on BR($t \to bH^+$) for charged Higgs production from top quark decays as a function of m_{H+}, assuming BR($H^+ \to \tau\,\nu$) = 1

including all systematic uncertainties (luminosity, trigger, reconstruction and identification efficiencies, energy/momentum resolution, MC generation uncertainties, uncertainties from fake lepton identification, etc.)

$H^{\pm} \rightarrow \tau_{lep}\nu$ + jets analysis

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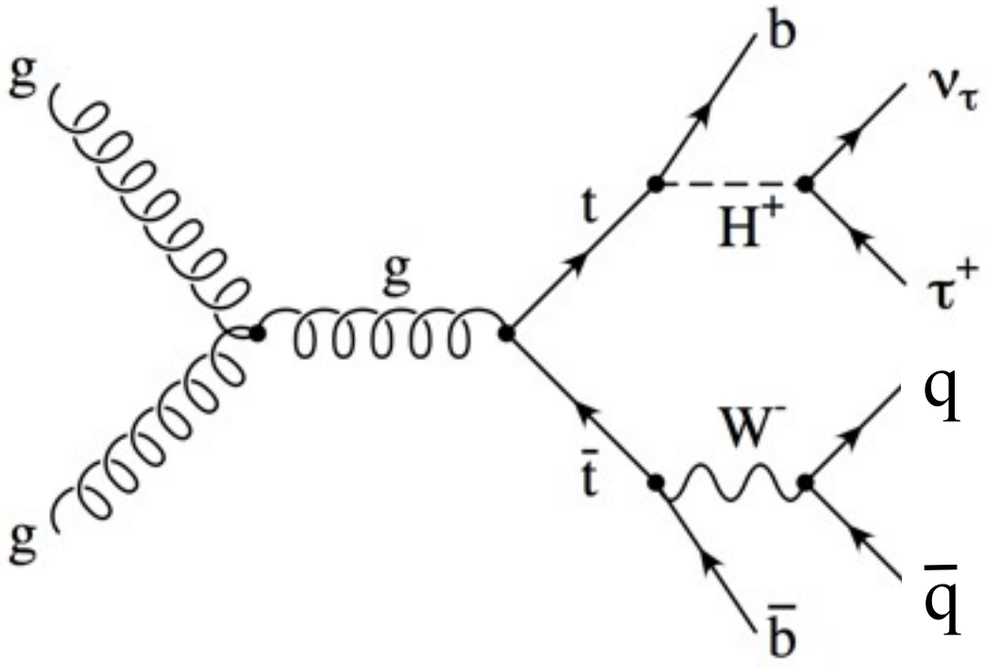
$H^{\pm} \rightarrow \tau_{lep}\nu$ + jets

Assumptions made in the following analysis:
- model-independent search of 90 GeV < m_{H+} < 160 GeV
- assumed BR($H^+ \rightarrow \tau\ \nu$) = 1 (unless stated otherwise)



Analysis carried out with an integrated luminosity of 4.6 fb^{-1} at $\sqrt{s}$ = 7 TeV

- Cut-based selection:
  - single lepton trigger
  - exactly 1 isolated e/μ, veto events with τ_{had}
  - ≥ 4 jets, exactly 2 of them are b-jets
  - Missing Energy: discriminate between E_T^{miss} from isolated neutrinos and poorly reconstructed leptons

- Reconstruction of hadronic top:
  - events minimising the χ^2 function, discard events with $\chi^2 > 5$

$$\chi^2 = \frac{(m_{jjb} - m_{top})^2}{\sigma_{top}^2} + \frac{(m_{jj} - m_W)^2}{\sigma_W^2},$$

(σ_{top} = 17 GeV, σ_W = 10 GeV)

- Non-negligible background contribution from non-isolated leptons:
  - data-driven background estimation

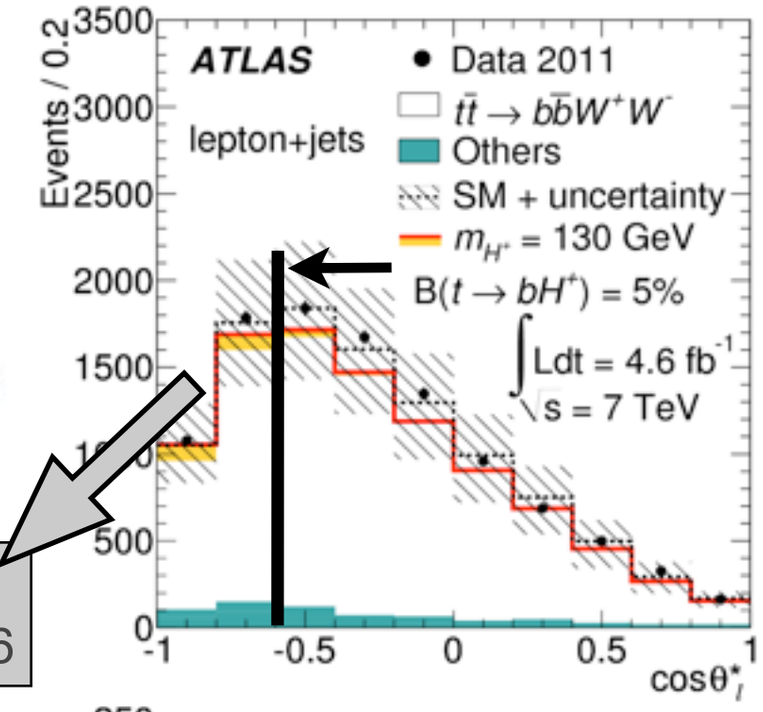
$H^+ \rightarrow \tau_{lep}\nu$ + jets: Discriminating Variables

- Reconstruction of discriminating variables after selection cuts:
  - Invariant mass $m_{b\ell}$ of b-jet and charged lepton ℓ:

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

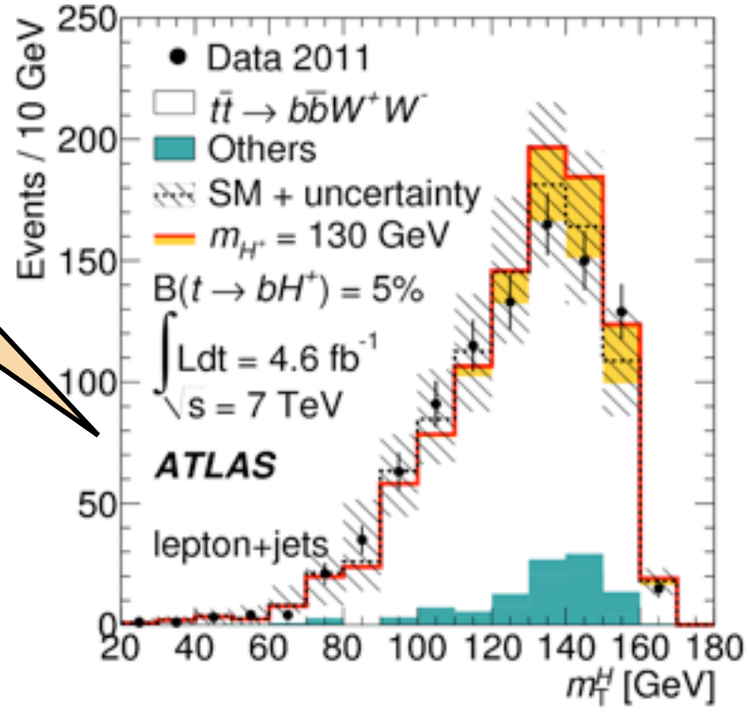
  - Higgs transverse mass

$$(m_{\text{T}}^H)^2 = \left(\sqrt{m_{\text{top}}^2 + (\vec{p}_{\text{T}}^{\,l} + \vec{p}_{\text{T}}^{\,b} + \vec{p}_{\text{T}}^{\,\text{miss}})^2} - p_{\text{T}}^b\right)^2 - \left(\vec{p}_{\text{T}}^{\,l} + \vec{p}_{\text{T}}^{\,\text{miss}}\right)^2$$



signal region:
cos Θ_ℓ* < -0.6

- shown in signal region:
  - cosΘ_ℓ* < -0.6
  - m_T^W < 60 GeV with: $m_{\text{T}}^W = \sqrt{2p_{\text{T}}^l E_{\text{T}}^{\text{miss}}(1 - \cos\Delta\phi_{l,\text{miss}})}$
    (suppress background from events where W decays directly to electron/muon)



Good agreement between data and SM expectation!

Systematic Uncertainties

Systematic uncertainties arising from

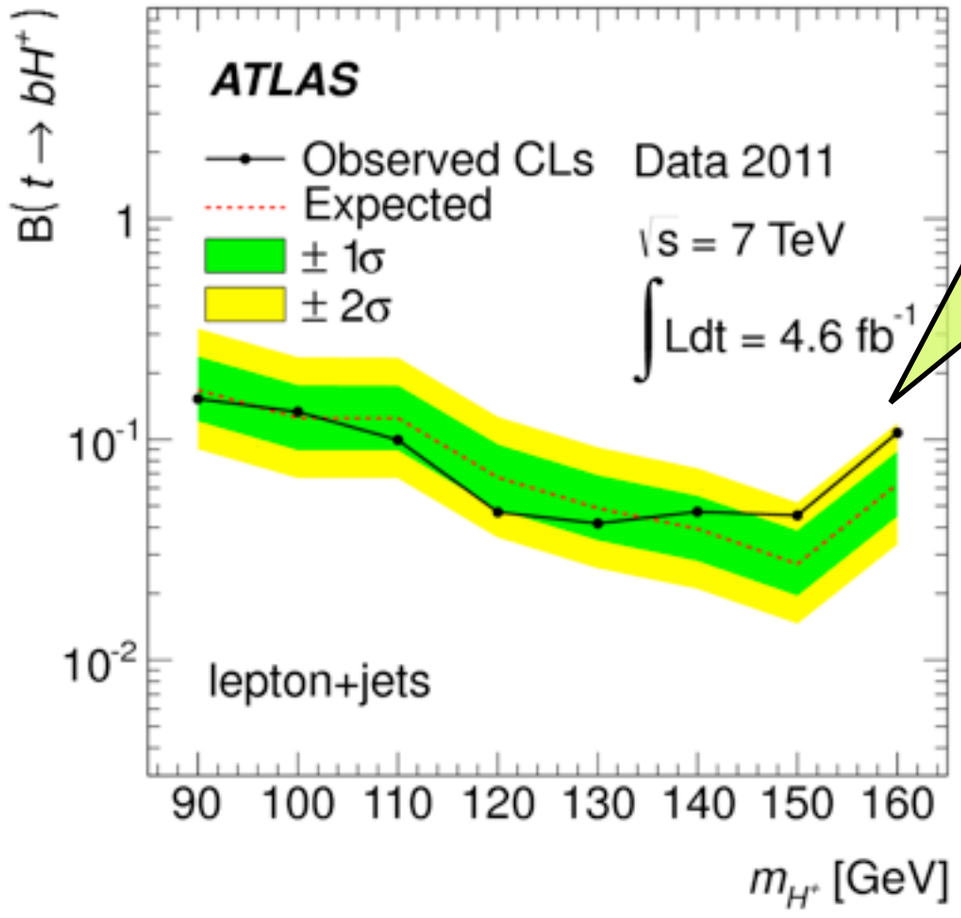
- generation of $t\bar{t}$ events
- data-driven background estimates

with main uncertainty arising from simulated sample used for subtraction of true leptons in the determination of misidentification probabilities

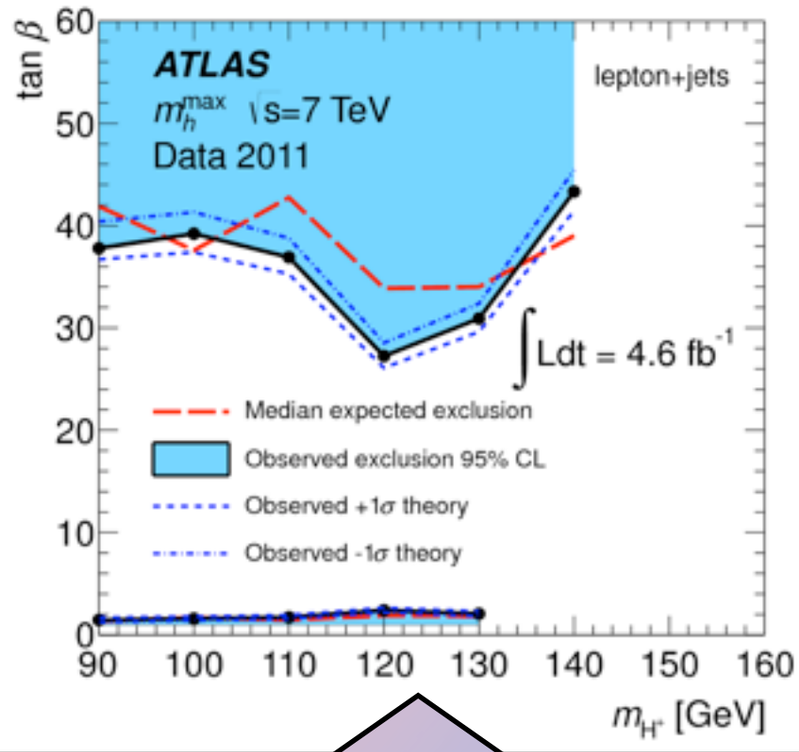
Source of uncertainty	Normalisation uncertainty
lepton+jets:	
Generator and parton shower ($b\bar{b}WH^+$, signal region)	10%
Generator and parton shower ($b\bar{b}W^+W^-$, signal region)	8%
Generator and parton shower ($b\bar{b}WH^+$, control region)	7%
Generator and parton shower ($b\bar{b}W^+W^-$, control region)	6%
Initial and final state radiation (signal region)	8%
Initial and final state radiation (control region)	13%

Source of uncertainty	Normalisation uncertainty
lepton+jets: lepton misidentification	
Choice of control region	6%
Z mass window	4%
Jet energy scale	16%
Jet energy resolution	7%
Sample composition	31%

$H^+ \rightarrow \tau_{lep}\nu$ + jets : Results



Expected and observed 95% CL exclusion limits on BR($t \rightarrow bH^+$) for charged Higgs production from top quark decays as a function of m_{H+}, assuming BR($H^+ \rightarrow \tau\,\nu$) = 1



Combination of results from the 3 different channels τ_{lep} + jets, τ_{had} + lepton, τ_{had} + jets
→ see Patrick's talk for more details!

95% CL exclusion limits on tan β as a function m_{H+}, shown in the context of the MSSM scenario m_h^{max} for the region $1 < \tan\beta < 60$ in which reliable theoretical predictions exist, relaxing the assumption of BR($H^+ \rightarrow \tau\,\nu$) = 1

$H^+ \rightarrow \tau_{lep}\nu$ + jets : Summary

- ATLAS collaboration has performed a model-independent search for a charged Higgs bosons in decays of pair-produced top quarks using 4.6 fb^{-1} with $\sqrt{s}$ = 7 TeV

- BR($H^+ \rightarrow \tau\nu$) = 1 is assumed and 3 different final states were considered
  - Results have been presented in one of the three channels: $H^+ \rightarrow \tau_{lep}\nu$ + jets

- In the absence of excess of events from SM expectations, combined 95% C.L. upper limits are set on BR($t \rightarrow bH^+$): 5% (1%) for m(H^+) = 90 (160) GeV
  - Improvement over upper limits from Tevatron (15-20%)
  - arXiv:0907.1269 (CDF), arXiv:0908.1811 (D0)

$H^{\pm} \rightarrow c\bar{s}$ analysis

ATLAS-CONF-2011-094

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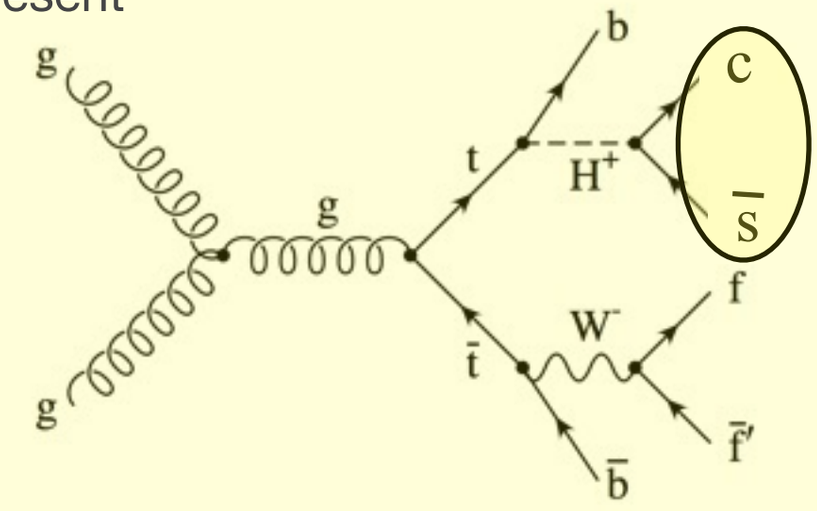
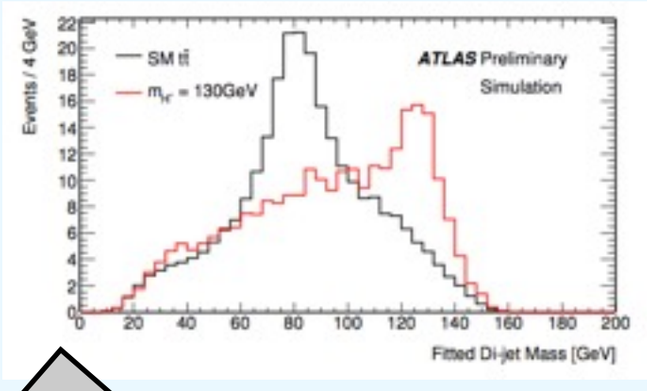
$H^{\pm} \rightarrow c\bar{s}$: Analysis Overview

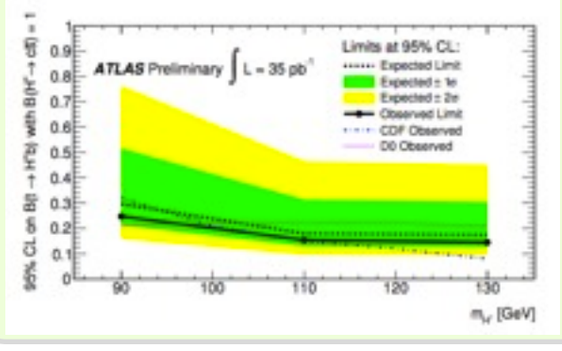
Dominant decay mode at low tan β is $H^{+} \rightarrow c\bar{s}$
→ complementary to $H^{+} \rightarrow \tau\nu$

Cut-based event selection of semi-leptonic $t\bar{t}$ events
→ ensure that final state objects are present



Kinematic fit: full reconstruction of $t\bar{t}$ events
→ reduction of width of W and H^{+} mass distribution

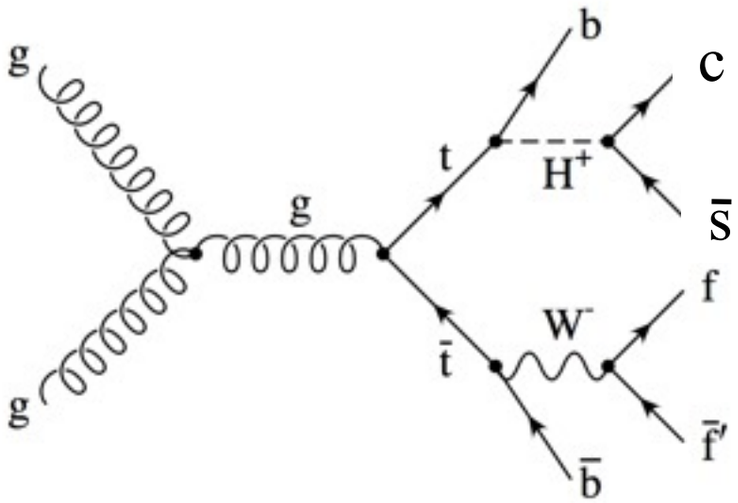




Data Interpretation:
→ discovery or 95% CL Limits

$\sqrt{s}$ = 7 TeV,
integrated luminosity of 35 pb^{-1}

$H^+ \rightarrow c\bar{s}$: Backgrounds & Event Selection



- Dominant background: $t\bar{t}$ events (~90%)
  - with one W decaying leptonically and the other W into light quarks (MC estimation)

- Non-$t\bar{t}$ backgrounds (~10%)
  - single top quark events (MC estimation)
  - W/Z+light/heavy-jets (MC estimation)
  - QCD multi-jet events (data driven methods: matrix method for muon+jets channel, binned likelihood template fit for electron+jets channel)

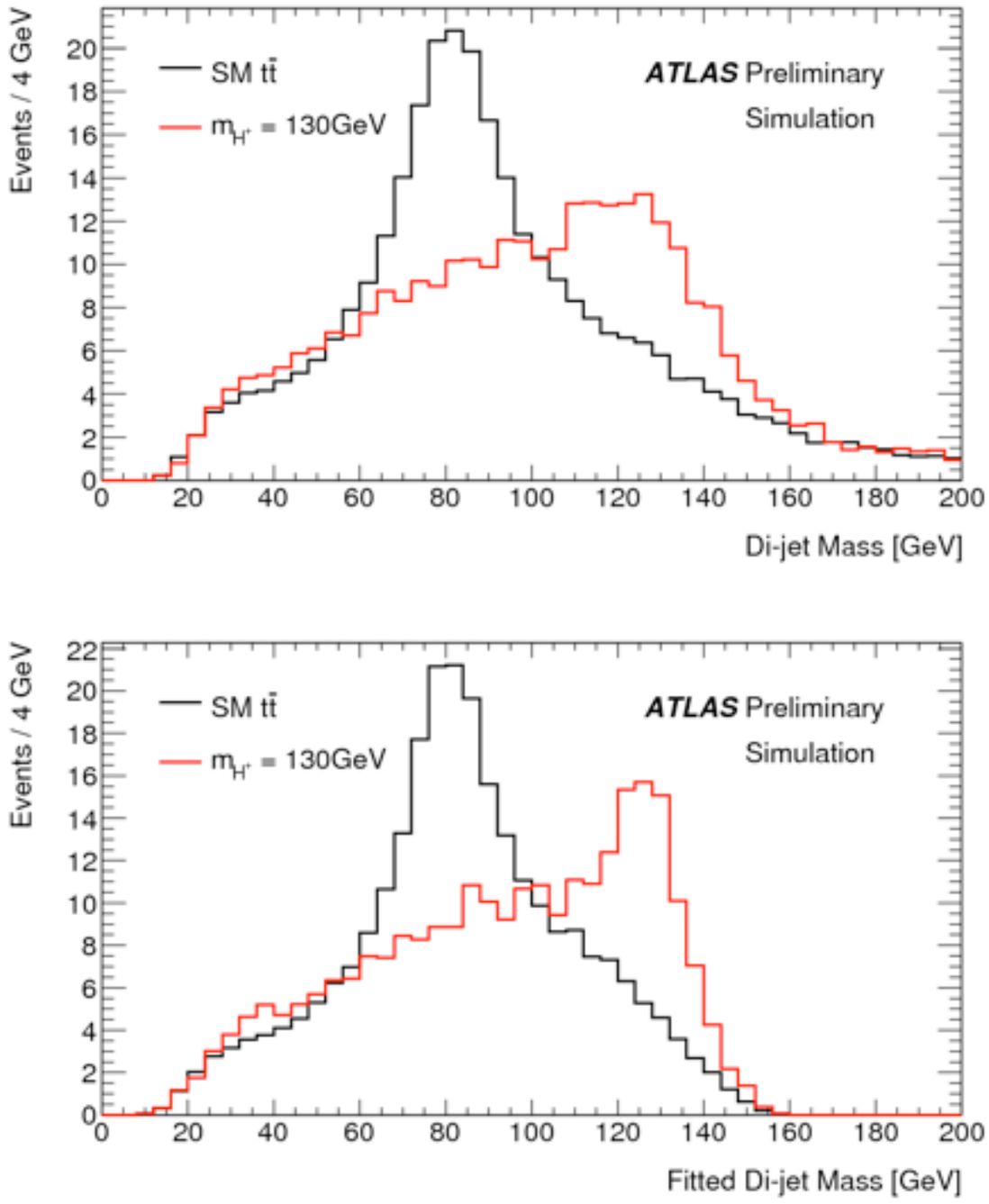
- Cut-based selection of semi-leptonic $t\bar{t}$ events
  - single lepton trigger
  - exactly 1 lepton matching the trigger object
  - at least 4 jets (W+jet background reduction)
    - at least one jet identified as b-jet via secondary vertex algorithm
  - Suppression of QCD multi-jet events:
    - $E_T^{miss} > 20$ (35) GeV for muon (electron) channel
    - $M_T(W) > 25$ GeV for electron channel
      $E_T^{miss} + M_T(W) > 60$ GeV for muon channel

$$M_T(W) = \sqrt{2 * p_T^{lepton} * p_T^{\nu} * (1 - \cos\Delta\phi)}$$

$H^{\pm} \rightarrow c\bar{s}$: Kinematic Fit

- To reconstruct the mass of H^+ candidates, the two jets from H^+ need to be identified
  - kinematic fitter used to identify and reconstruct mass of di-jets from W/H^+ candidates
    → full reconstruction of $t\bar{t}$ event
    - requires correct assignment of jets from top quark decays to the four original partons
    - constrain W and top quark masses to their PDG values, with floating jet/lepton energy within their measured resolutions
    - best combination found by minimising χ^2 for each assignment of jets to quarks
    - remove poorly reconstructed $t\bar{t}$ events with χ^2>20
    - selection efficiency of 82% for $t\bar{t}$ events

→ reduction of the width and tails of the di-jet mass distribution
→ good discrimination between the mass peaks of the W boson from SM decays and H^+ boson



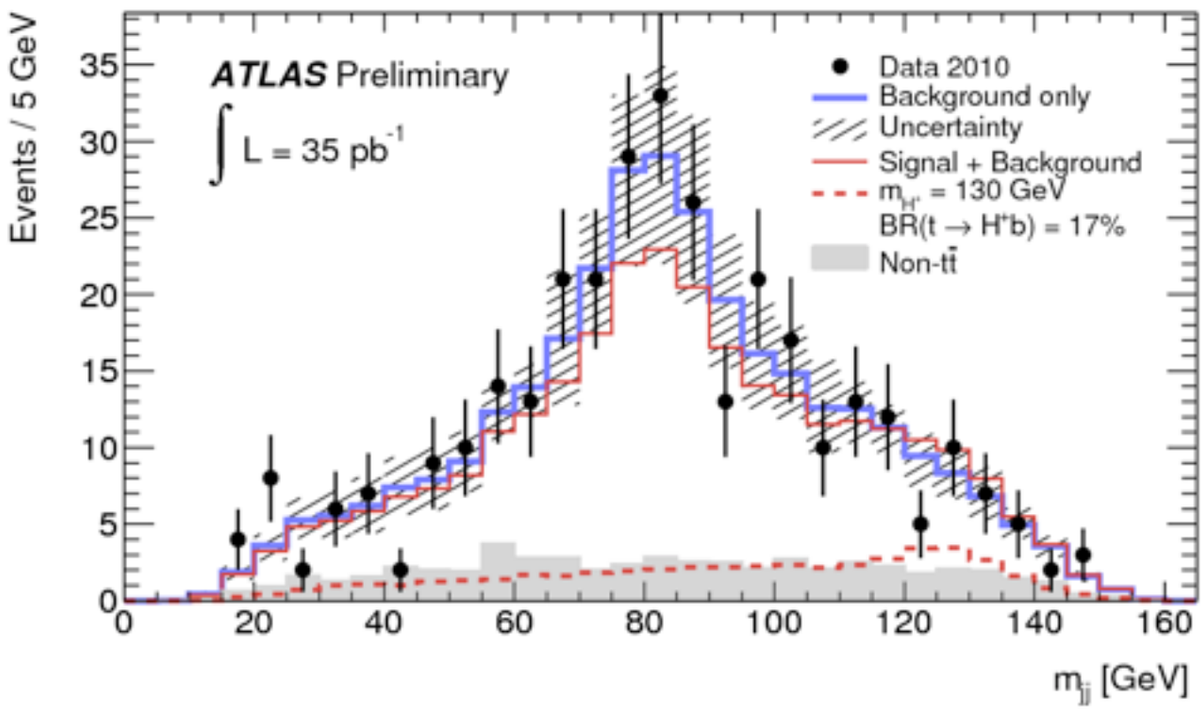
$H^{\pm} \rightarrow c\bar{s}$: Systematic Uncertainties & Results

- Systematic Uncertainties:
  - table shows effect of systematic uncertainties on expected number of $t\bar{t}$ background and signal events

- Number of observed events in data after selection agrees well with expectation from SM backgrounds
  - good agreement of data and SM expectation in di-jet mass distribution

  → extraction of upper limits on BR($t \rightarrow H^{+}b$) as function of charged Higgs mass

Systematic Source	
Jet energy scale	+11, −13% (SM $t\bar{t}$)
	+9, −12% (signal)
b-Jet energy scale	±0.5%
Jet energy resolution	±1%
b-tagging efficiency	+4, −9%
MC generator	±4%
Parton shower	±3%
ISR/FSR	±1%
Additional Interactions	±4%
Luminosity	±3.4%
Electron reconstruction	±1.6%
Muon reconstruction	±0.2%
Electron trigger	±0.2%
Muon trigger	±0.5%
$t\bar{t}$ cross section	+7, −9%
t quark mass	±7%

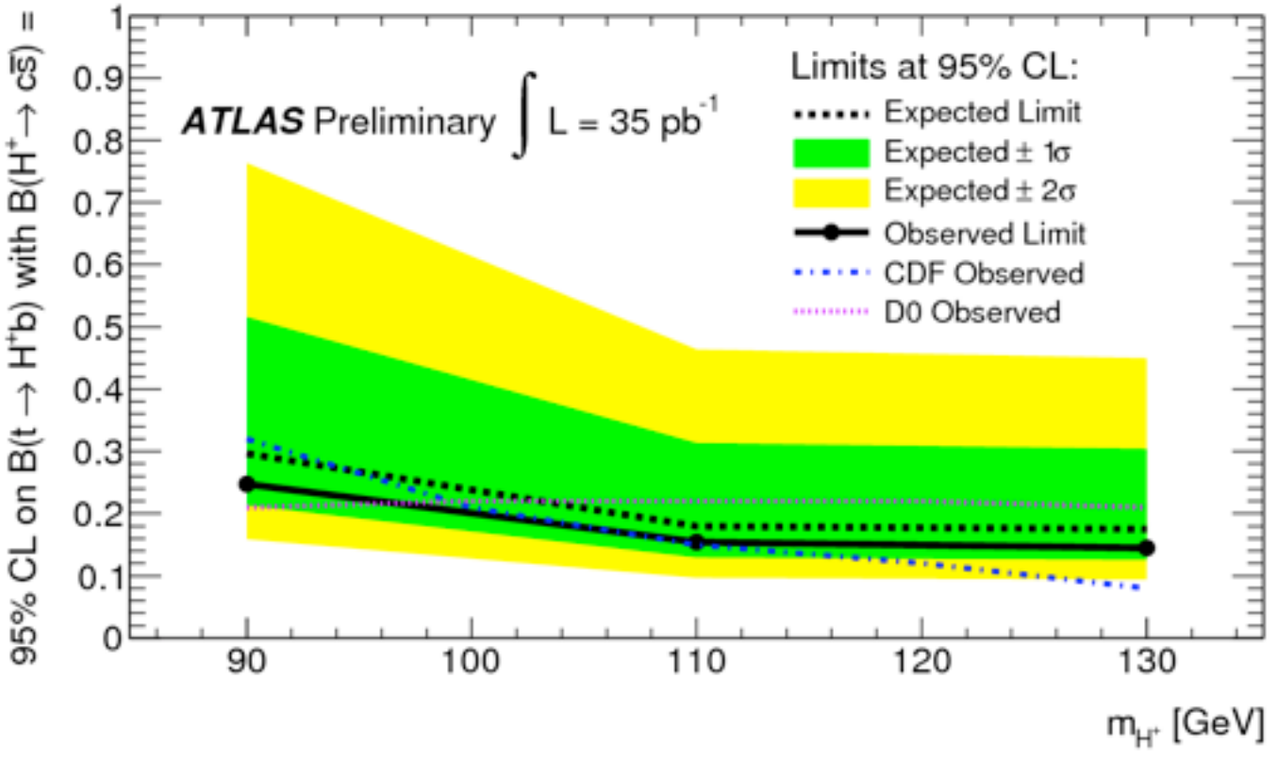


Channel	Muon	Electron
Data	193	130
SM $t\bar{t} \rightarrow W^{+}bW^{-}\bar{b}$	156^{+24}_{-29}	106^{+16}_{-20}
W/Z + jets	17 ± 6	9 ± 3
Single top	7 ± 1	5 ± 1
Diboson	0.30 ± 0.02	0.20 ± 0.02
QCD multijet	11 ± 4	6 ± 3
Total Expected (SM)	191^{+26}_{-30}	127^{+17}_{-21}

$H^{\pm} \rightarrow c\bar{s}$: Limits

- Expected and observed 95% CL limits on the BR($t \rightarrow H^{+}b$)
  - limits calculated using CL_s limit setting procedure

Higgs Mass	Expected limit	Observed limit
90 GeV	0.30	0.25
110 GeV	0.18	0.15
130 GeV	0.17	0.14



- Extracted 95% CL upper limits on BR($t \rightarrow H^{+}b$)
  - compared with expected results
  - compared with results from Tevatron
  - assuming BR($H^{+} \rightarrow c\bar{s}$) = 1

$H^{\pm} \rightarrow c\bar{s}$: Summary

- Presented search of charged Higgs boson decaying via $c\bar{s}$ and produced via decay of top quarks
- Results are consistent with null Higgs hypothesis
  - di-jet mass distribution in good agreement with expectation from SM
- Limits are within one standard deviation of the expected limits and range from BR = 0.25 to 0.14 for m_{H+}= 90 to 130 GeV
  - assuming BR($H^+ \rightarrow c\bar{s}$) = 1
- First limits on charged Higgs boson in this channel from LHC

$H^{\pm\pm} \rightarrow \mu^{\pm}\mu^{\pm}$ search

Phys. Rev. D 85, 032004 (2012)

Introduction

- Search for anomalous production of prompt like-sign muon pairs
  - events with two high-p_T, prompt, like-sign leptons are rare in SM
  - but occur with enhanced rate in several models of new physics:
    - supersymmetry
    - universal extra dimensions
    - left-right symmetric models
    - Higgs triplet models etc.
  - most of these models would result in an excess of like-sign di-muons over the background but no kinematic features
- BUT: doubly charged Higgs bosons ($H^{\pm\pm}$) would be observed as a narrow resonance in the di-muon mass spectrum

In the following presented analysis:

- events containing like-sign muon pairs are selected
- invariant di-muon mass distribution is compared to the SM prediction
- search for a narrow di-muon resonance is also carried out
- constraints on the $H^{\pm\pm}$ mass as a function of its BR to muons are placed

Event Selection & Backgrounds

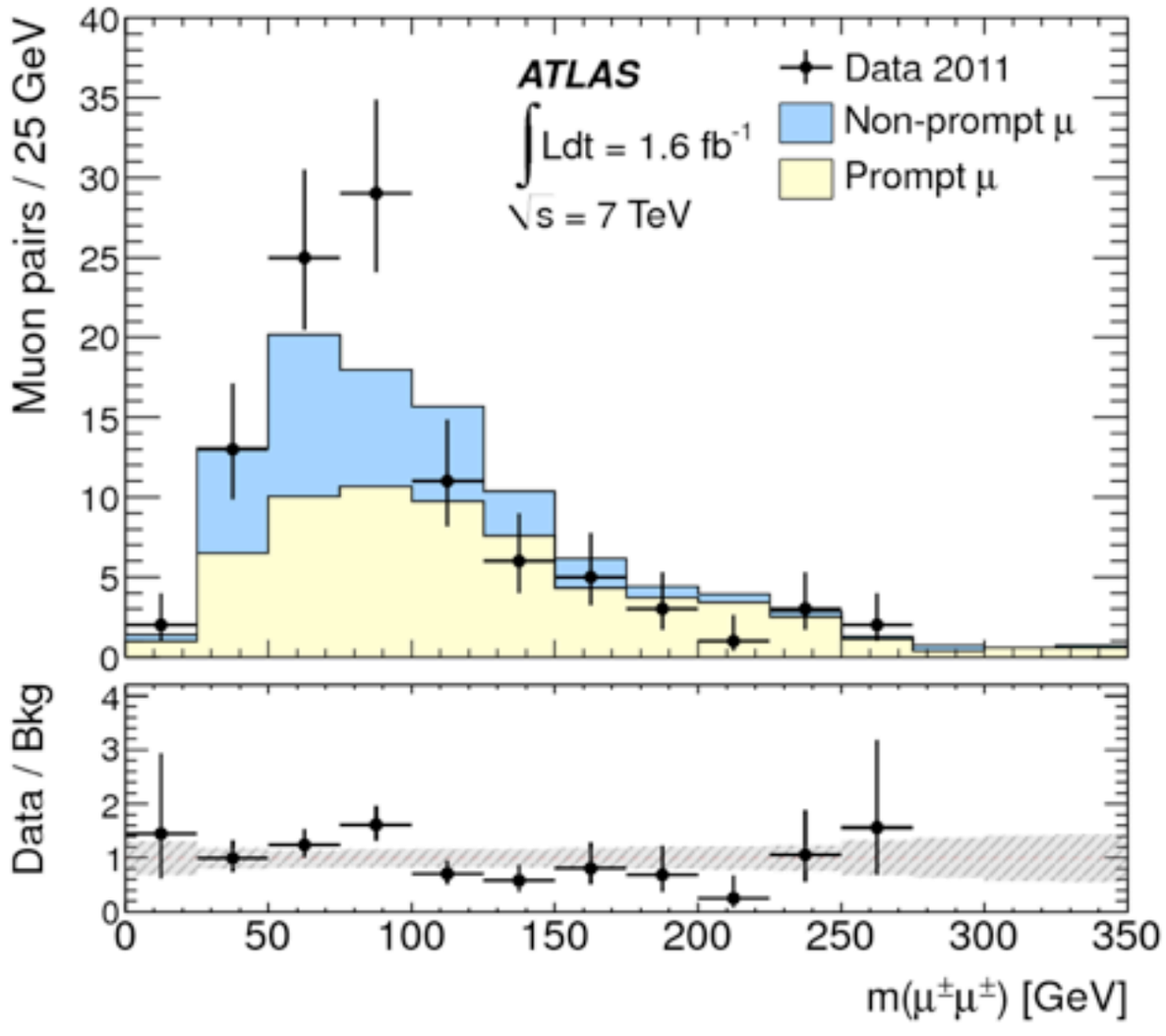
- Using data sample corresponding to 1.6 fb^{-1} recorded at $\sqrt{s}$ = 7 TeV

- Event selection:
  - Single muon triggers with p_T thresholds of
    - p_T > 18 GeV for muon
  - at least 2 muons with same charge
    - allow multiple pairs per event
  - $m_{\mu\mu}$ > 15 GeV to exclude low-mass resonances (e.g. J/Psi, Upsilon mesons)

- Backgrounds:
  - prompt like-sign di-muons processes
    - WZ, ZZ, like-sign WW, also $t\bar{t}W$
    - expected contribution is derived from MC simulation normalised to cross-section calculations performed at NLO
  - background caused by muons from hadronic decays
    - primarily from semi-leptonic b- and c-hadron decays
    - data-driven background estimation using matrix method
  - background from processes with two prompt opposite sign muons
    - due to charge misidentification of one of the muons
    - processes include Drell-Yan, $t\bar{t}$, WW production
    - background derived from MC simulation → negligible in relevant mass range

Data & Background Comparison

- Invariant mass distributions
  - data agree with background within systematic uncertainties (mainly MC cross-section, PDFs and uncertainty on measurement of the fraction of non-prompt muons passing isolation cuts)
  - no excess observed

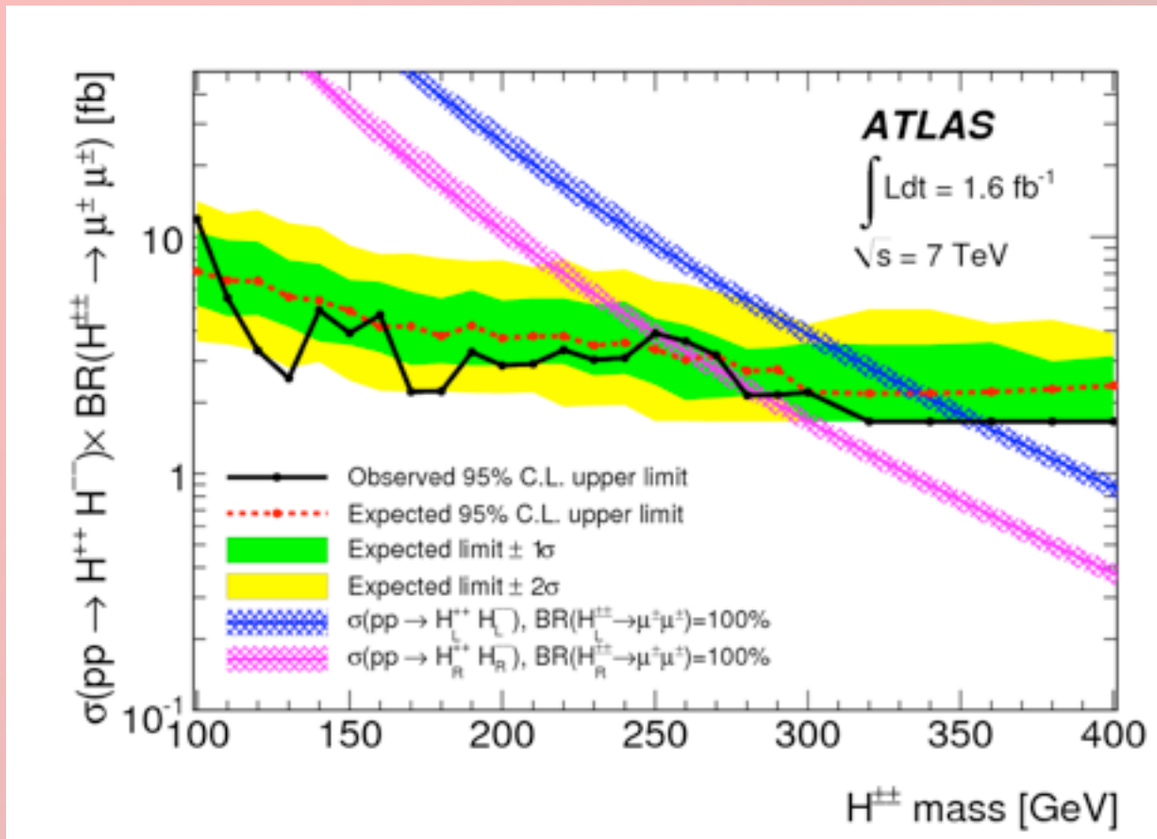


Limits

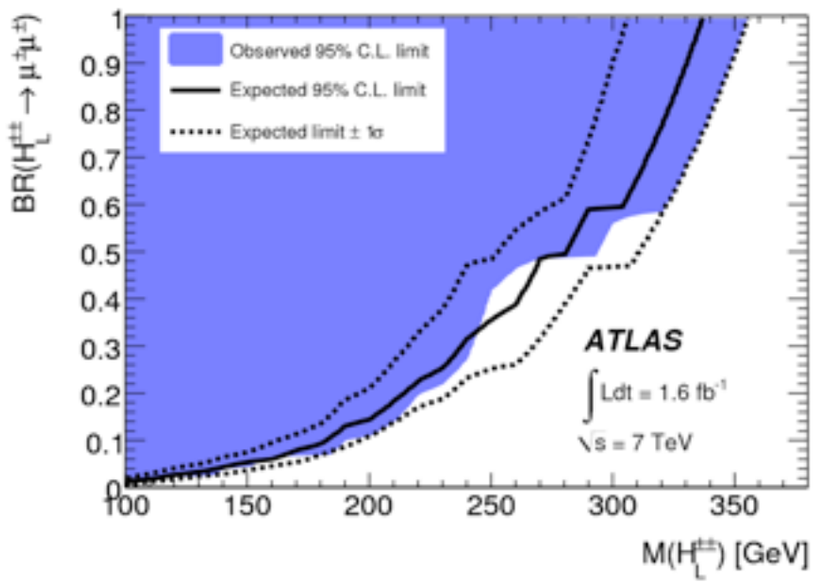
Limit on cross-section times branching ratio

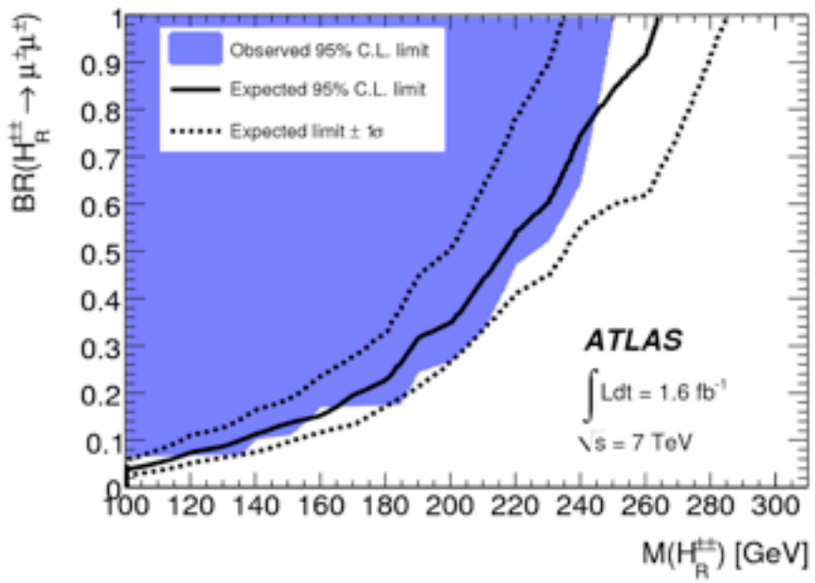
- derived from limit on number of muon pairs with invariant mass within 10% of considered $H^{\pm\pm}$ mass

→ 95% expected and observed upper limits on σ x BR as function of $H^{\pm\pm}$ mass



also shown: exclusion region at 95% CL of the $H^{\pm\pm}$ mass as a function of the BR to muon pairs for left- and right-handed $H^{\pm\pm}$ bosons





Summary

- Inclusive search for production of pairs of prompt like-sign muons presented
  - integrated luminosity of 1.6 fb^{-1}
- Data agree with background expectation
  - no sign of new physics has been found
- Constraints are placed on doubly charged Higgs boson production
  - lower mass limit with a 100% (33%) branching ratio to muons is
    - 355 (244) GeV for $H^{\pm\pm}$ bosons coupling to left-handed fermions
    - 251 (209) GeV for $H^{\pm\pm}$ bosons coupling to right-handed fermions