Search for Charged Higgs Bosons at the LHC

The ATLAS and CMS Detectors

ATLAS, July 2007

CMS, Jan 2007

ATLAS
Toroid Magnets  Solenoid Magnet  SCT Tracker  Pixel Detector  TRT Tracker

CMS
Outline

• The Charged Higgs Boson (H⁺)

• H⁺ channels investigated for CMS and/or ATLAS
  (in detail: publications from 2006/07)
  – H⁺ from top quark decays
  – H⁺ from gg- and gb-fusion
  – “exotic” channels

• Discovery reach
The Charged Higgs Boson

- **Two Higgs Doublet Model (THDM):** 5 Higgs Bosons $A^0$, $h^0$, $H^0$, $H^\pm$.
  - Simple Extension to SM
  - required Higgs Sector of MSSM
  - possible in other SUSY models (fermiophobic models, ...)
  or: $H^+$ from triplets; several doublets/triplets; Little Higgs; ...

- Charged Higgs searches currently focus on generic THDM (producing cross section limits) and MSSM scenarios
  (unless stated otherwise, the following plots/numbers refer to the $m_h$-max MSSM scenario)
  - MSSM Higgs sector: at tree-level 2 free parameters, e.g.:
    - $m_{H^+}$ and $\tan \beta$ (Ratio of the Higgs doublet vacuum expectation values)

- The Charged Higgs Boson ($H^+$) is a **heavy** charged colorless scalar
  → **Production** Modes (LHC):
    - $t \rightarrow H^+ b$
    - $gg \rightarrow tbH^+$
    - $gb \rightarrow tH^+$
  → **Decay** Modes:
    - $H^+ \rightarrow tb$
    - $H^+ \rightarrow \tau \nu$
    - $H^+ \rightarrow cs$
  
  \(^1\)e.g. $m_h$-max MSSM, all $\tan \beta$: $m_{H^+} > 80$ GeV [1]
Overview: \( m_{H^+} < m_{\text{top}} \)

- Production: top quark decays, via \( tt\bar{t} \rightarrow bW^- bH^+ \)
- \( \text{BR}(t \rightarrow bH^+) \) depends on \( m_{H^+} \) and \( \tan \beta \)

- \( \text{BR}(H^+ \rightarrow \tau \nu) \approx 1 \)

> Main channels of interest:

<table>
<thead>
<tr>
<th>( H^+ ) Decay</th>
<th>W Decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau \nu, \tau \rightarrow \text{had} )</td>
<td>( qq )</td>
</tr>
<tr>
<td>( \tau \nu, \tau \rightarrow \text{had} )</td>
<td>( lv )</td>
</tr>
<tr>
<td>( \tau \nu, \tau \rightarrow \text{lep} )</td>
<td>( qq )</td>
</tr>
</tbody>
</table>
$tt\rightarrow H^+ bWb$, $H^+ \rightarrow \tau^+_{\text{had}} \nu, W \rightarrow l\nu$ (1)

CMS NOTE 2006/056, Baarmand/Hashemi/Nikitenko

**Signature:**
- lepton
- tau-jet
- 2 b-jets
- missing $E_T$

**Main Backgrounds:**
- $tt\bar{t}$ with one $t \rightarrow bl\nu$
- $W+3$ jets with $W \rightarrow l\nu$

**Event Selection:**
- a triggered lepton
- $\geq 3$ jets with $E_T > 40$ GeV
- $Q(l) + Q(\tau) = 0$
- $\tau$-jet with $E_T > 40$ GeV and $p_{\text{track}}/E_{\tau} > 0.8$
- Missing $E_T > 70$ GeV

**Exploited difference signal/$tt\bar{t}$:**
- $m_{H^+} > m_W$: $p_T^{\tau}$, $E_T^{\text{miss}}$ larger
- Spin: $H^+ \rightarrow 0$, $W \rightarrow 1$
tt→H⁺bWb, H⁺→τ_had ν, W→lν (2)

CMS NOTE 2006/056, Baarmand/Hashemi/Nikitenko

After all selection cuts (tan β=20):

<table>
<thead>
<tr>
<th>m_{H^+} (GeV)</th>
<th>σ×BR [fb]</th>
<th>Efficiency</th>
<th>Events/10fb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>140</td>
<td>10700</td>
<td>4.8x10⁻³</td>
<td>510</td>
</tr>
<tr>
<td>150</td>
<td>5060</td>
<td>5.0x10⁻³</td>
<td>254</td>
</tr>
<tr>
<td>160</td>
<td>1830</td>
<td>5.0x10⁻³</td>
<td>92</td>
</tr>
<tr>
<td>tt→lνν bb</td>
<td>2.6x10⁴</td>
<td>2.0x10⁻³</td>
<td>516</td>
</tr>
<tr>
<td>tt→lν/νbb</td>
<td>4.0x10⁴</td>
<td>7.4x10⁻⁴</td>
<td>293</td>
</tr>
<tr>
<td>tt→lνqqbb</td>
<td>2.5x10⁵</td>
<td>1.5x10⁻⁴</td>
<td>366</td>
</tr>
<tr>
<td>W+3 jets, W→lν</td>
<td>8.4x10⁵</td>
<td>1.3x10⁻⁵</td>
<td>107</td>
</tr>
</tbody>
</table>

Main Systematics Sources:
- ttbar cross section
- luminosity measurement
- τ-tagging (efficiency/rejection)
- b-tagging (efficiency/rejection)
- jet energy scale

Discovery Sensitivity:
- tan β>50: up to almost m_{top}
- all tan β: for m_{H^+}<130 GeV
tt→H⁺bWb, H⁺→τ⁺ν, W→qq (1)

Signature:
- tau-jet
- missing E_T
- 2 b-jets
- hadronic W/top

Main Backgrounds:
- ttbar
- QCD

Exploited difference signal/ttbar:
- m_{H⁺} > m_W: p_T^τ, E_T^{miss} larger
- Spin: H⁺→0, W→1

Event Selection:
- tau+MET or jet+MET trigger
- = τ-jet, p_T^τ > 25 GeV
- =2 b-jets, p_T^{b1} > 35 GeV, p_T^{b2} > 20 GeV
- ≥2 light jets, p_T^{j1} > 30 GeV, p_T^{j2} > 20 GeV
- Missing E_T > 45 GeV
- W/top Reco (20/40 GeV mass window)
- ttbar pattern (angle/p_T relations of tops)
- Veto on isolated leptons
- p_T^τ / p_T^b > 0.8 (H⁺ side)
- H⁺ Transverse Mass
tt→H⁺bWb, H⁺→τ_hadν, W→qq (2)

ATL-PHYS-2003-038, Biscarat/Dosil

H⁺ Transverse Mass
(m_H⁺ = 127 GeV, tan β=30)

After all selection cuts (tan β=30):

<table>
<thead>
<tr>
<th>m_H⁺ (GeV)</th>
<th>Events/10 fb⁻¹ incl. systematics</th>
</tr>
</thead>
<tbody>
<tr>
<td>85</td>
<td>5100</td>
</tr>
<tr>
<td>127</td>
<td>4200</td>
</tr>
<tr>
<td>140</td>
<td>2900</td>
</tr>
<tr>
<td>160</td>
<td>410</td>
</tr>
<tr>
<td>ttbar</td>
<td>2300</td>
</tr>
<tr>
<td>QCD</td>
<td>20</td>
</tr>
</tbody>
</table>

Discovery Sensitivity (30 fb⁻¹):
- all tan β: up to almost m_{top}

N.B.: This is Fast Simulation!
... an ATLAS study using a more realistic simulation is on the way.
Overview: $m_{H^+} > m_{\text{top}}$

- Production: **gg/gb-fusion**
  
  $gg \rightarrow tbH^+$, $gb \rightarrow tH^+$

  (→double-counting term, resolved by MC Generator “Matchig”)

- $\text{BR}(H^+ \rightarrow tb) \approx 0.8-1$
  
  → Main channels of interest:

<table>
<thead>
<tr>
<th>$H^+$ Decay</th>
<th>W Decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau\nu$, $\tau \rightarrow \text{had}$</td>
<td>$qq$</td>
</tr>
<tr>
<td>$tb$</td>
<td>$l\nu$ &amp; $qq$ (2 $W$s)</td>
</tr>
</tbody>
</table>

For each channel, only the most recent CMS or ATLAS study is presented in detail; reference to the study of the other experiment is given in [brackets], differences to the presented publication are briefly discussed and results are given
\textbf{Signature:}
- 3-4 b-jets
- lepton
- 2 W, 2 top

\textbf{Main Backgrounds:}
- ttbar+b, ttbar+bbar
- ttbar+jet(s)

\textbf{Exploited difference signal/ttbar+X:}
- \(m_{H^+}\) invariant mass
- up to 4 b-jets

\textbf{Event Selection, for 3 (4) b-tag-analysis:}
- a muon, \(p_T^{\mu}>20\) GeV
- at least 5 (6) jets, \(p_T^{\mu}>25\) GeV
- at least 3 (4) b-tags
- kinematic fit imposing mass constraints for both Ws and both top quarks
- LH to suppress combinatorial background
- 3 b-tags: LH to suppress ttbar+X using
  a) \(p_T\): softest jet from W, b) \(\chi^2\) of the fit,
  c) discriminator: b from \(H^+\), d) \(E_T^{j6}/E_T^{j5}\)
  4 b: \(b\)-discriminator: b from \(H^+\), spectator-b
Conclusion: Even assuming very low systematic background uncertainties:
No sensitivity in the MSSM space.
(Similar conclusions for ATLAS from a fast simulation-based study)
M. Flechl: Search for Charged Higgs Bosons at the LHC

**gg/gb→tH⁺[b], H⁺→τ⁺ν, W→qq (1)**

ATL-PHYS-PUB-2007-006, Mohn/Flechl/Alwall
[CMS NOTE 2006/100, Kinnunen, see slide 19]

**Signature:**
- hard tau-jet
- large missing $E_T$
- hadronic W, top
- 1-2 b-jets

**Main Backgrounds:**
- ttbar
- W+jets
- QCD

**Exploited difference signal/ttbar:**
- $m_{H^+}$ invariant mass
- $\Rightarrow$ hard $\tau$-jet, high missing $E_T$

**Event Selection:**

*(mass range: low/medium/high)*
- one hard $\tau$-jet ($p_T^\tau>65/80/100$ GeV)
- $E_T^{\text{miss}}>120/135/165$ GeV
- $\geq 3$ more jets (=1 b-tagged)
- Veto on isolated leptons
- W/top-Reco (25 GeV-mass window)
- $p_T^\tau / p_T^{\text{add. Jet}} > 6.0/5.5/5.0$
- azimuthal angle ($p_T^\tau, p_T^{\text{miss}}$)
gg/gb→tH⁺[b], H⁺→τ⁺ν, W→qq (2)

ATL-PHYS-PUB-2007-006, Mohn/Flechl/Alwall
[CMS NOTE 2006/100, Kinnunen]

Event Generator MATCHIG allows for the 1st time a matched production gg/gb and thus a consistent treatment of the transition region \( m_{H^+} \approx m_{t\ell} \)

After all selection cuts (\( \tan \beta = 35 \)):

<table>
<thead>
<tr>
<th>( m_{H^+} ) (GeV)</th>
<th>Events/30fb(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>165</td>
<td>57 5.4</td>
</tr>
<tr>
<td>175</td>
<td>37 5.4</td>
</tr>
<tr>
<td>300</td>
<td>11 1.1</td>
</tr>
<tr>
<td>400</td>
<td>7 1.1</td>
</tr>
</tbody>
</table>

High S/B ratio makes the channel less sensitive to systematics than \( H^+\rightarrow tb \)

CMS: Fullsim Backgrounds, Trigger Simulation, no MATCHIG, some difference in cuts - see slide 19

Discovery Channel for a heavy \( H^+ \) at the LHC
More $H^+$ channels...

- $H^+ \rightarrow \chi_i^+ \chi_j^0$
  sensitive at the uncovered region $\tan \beta \approx 4-20$
  (of course heavily dependend on the SUSY scenario, and a previous understanding of the SUSY background and parameters)

- $H^+ \rightarrow W^0$, $H^+ \rightarrow WH^0$
  ATL-PHYS-99-025, ATL-PHYS-PUB-2005-017
  - significant cross section only for very small $\tan \beta$.
  - current studies show that even with known $m_{h^0}$ and high luminosity, no discovery reach is given

- $H^+$ sensitivity in $t\bar{t}$bar and single top cross section measurements
Discovery Reach

CMS and ATLAS Discovery Contours: MSSM, $m_h$-max scenario

<table>
<thead>
<tr>
<th>CMS</th>
<th>ATLAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$30 \text{ fb}^{-1}$</td>
<td>$300 \text{ fb}^{-1}$</td>
</tr>
<tr>
<td>with systematics</td>
<td>without systematics</td>
</tr>
<tr>
<td>Fullsim</td>
<td>Fastsim</td>
</tr>
</tbody>
</table>

N.B.: The currently approved discovery contours cannot be compared.

ATLAS update expected for end of this year.

The current studies suggest:

- $m_{H^+} < \approx m_{\text{top}}$: will be covered at the LHC (in worst case at high luminosity)
- $m_{H^+} > m_{\text{top}}$: sensitive only for high $\tan \beta$
Conclusions and Outlook

• Implications of current studies:
  - $H^+\rightarrow\tau\nu$ is the prime LHC $H^+$ discovery channel in the MSSM space (and could be the first BSM-signal and SUSY-glimpse we see)
  - $H^+\rightarrow tb$ does not have any MSSM discovery sensitivity
  - light $m_{H^+}$: the LHC experiments are sensitive to an MSSM $H^+$ up to $m_{H^+}$ values close to $m_{top}$
  - heavy $H^+$: high luminosity runs are needed. The medium tan $\beta$ region is not covered (might be accessible after a SUSY discovery)

• The future:
  - refine studies, understand systematics, identify control samples / sidebands, improve tools (b/$\tau$-tagging, ...)
  - first studies on $H^+\rightarrow\tau\nu$ with $\tau\rightarrow\ell\nu\nu$ are arriving
  - all presented channels+some more: currently investigated with Full Simulation for ATLAS, too => results end of this year
  - data!!!
The $m_h$-max scenario of the MSSM:

$M_2 = 200 \text{ GeV}$ \hspace{1cm} $\mu = 200 \text{ GeV}$ \hspace{1cm} $X_T = 2 \text{ TeV}$

$M_{\text{SUSY}} = 1 \text{ TeV}$ \hspace{1cm} $m_{\text{gluino}} = 800 \text{ GeV}$

$m_{H^+}$ and $\tan \beta$ are free parameters.
Differences between ATLAS and CMS Studies (1)

\textbf{gg/gb→tH^+[b], H^+→tb}

In SN-ATLAS-2004-042, as compared to CMS NOTE 2006/109:

- based on Fast Simulation
- no pile-up
- mass range $m_{H^+} = 200$-$800$ GeV investigated
- only investigates $gg→tbH^+$
- looks at muon \textit{and electron} decays of one of the Ws
- Likelihood to decrease combinatorial background, but no kinematic fit to the particle four-momenta
  - uses reconstructed angles, momenta and invariant mass
- different variables for background suppression:
  $$m_{b_0b_2} \cos(b_0, b_2) \cos(b_0 + b_2) \cos(b_0, b_2) \cos(t^{H^+}, H^+)$$
Differences between
ATLAS and CMS Studies (2)

\[ gg/gb \rightarrow tH^+[b], \ H^+ \rightarrow \tau_{\text{had}}\nu, \ W \rightarrow qq \]

In CMS NOTE 2006/100, as compared to ATL-PHYS-PUB-2007-006:

- Full Simulation used for backgrounds
- only \( gg \rightarrow tH^+[b] \) simulated (scaled to \( gg/gb \rightarrow tH^+[b] \) cross section)
- Simulation includes pile-up for low luminosity runs
- Poisson significance estimator used
- same optimisation for whole mass range \( (m_{H^+} = 170-600 \text{ GeV}) \)
- cut on \( p \) (leading track) / \( E \) (\( \tau \)-jet) > 0.8 (exploit \( \tau \) helicity correlations)
- Veto on additional central jets [instead of cut on \( p_T \) (additional jet)/\( p_T \) (\( \tau \)-jet)]
- no cut on the pseudorapidity of the \( \tau \)-jet
- trigger simulation applied
- differences in \( \tau \)-jet/b-jet/lepton reconstruction and tagging
References

[9] CMS NOTE 2006/100, Kinnunen