ATLAS Searches for Higgs Bosons
Beyond the Standard Model

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on behalf of the ATLAS Collaboration

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**The ATLAS Experiment at the CERN LHC**

**3-Level Trigger**
Reducing the rate from 40 MHz to 200-300 Hz

**Muon Spectrometer**
(|η|<2.7): Air-core toroids with gas-based muon chambers; Muon trigger and measurement with momentum resolution < 10% up to $p_\mu \sim 1$ TeV

**EM Calorimeter**
(|η|<3.2): Pb-LAr Accordion; allows for e/γ triggering, identification and measurement; E-resolution: $\sigma/E \sim 10%/\sqrt{E}$

**HAD calorimetry**
(|η|<5): hermetic and highly segmented; Fe/scintillator Tiles (central), Cu/W-LAr (fwd) Trigger and measurement of jets and missing $E_T$
E-resolution: $\sigma/E \sim 50%/\sqrt{E} \oplus 0.03$

**Inner Detector**
(|η|<2.5, $B=2T$): Si Pixels, Si strips, Transition Radiation detector (straws); Precise tracking and vertexing, allows for e/π separation; Momentum resolution: $\sigma/p_T \sim 3.8\times10^{-4}$ $p_T$ (GeV) $\oplus 0.015$
i.e. $\sigma/p_T < 2\%$ for $p_T < 35$ GeV
Recent Higgs Search Results in ATLAS

**Standard Model Higgs**

(Joost Vossebeld’s presentation from Tuesday)

- \(H \rightarrow \gamma \gamma\)
- \(H \rightarrow WW \rightarrow l\nu l\nu\)
- \(H \rightarrow WW \rightarrow l\nu qq\)
- \(H \rightarrow ZZ \rightarrow 4l\)
- \(H \rightarrow ZZ \rightarrow ll\nu\nu/llqq\)
- Combined Search (ATLAS-CONF-2011-112)

**Beyond the SM Higgs**

(this presentation)

- MSSM \(h/A/H \rightarrow \tau l\tau h\) (arXiv:1107.5003)
- \(H^+ \rightarrow cs\) (ATLAS-CONF-2011-094)
- \(H^+ \rightarrow \tau l\nu\) (ATLAS-CONF-2011-018)
- \(H^+ \rightarrow \tau_h\nu\) (ATLAS-CONF-2011-051)
2 Higgs doublets give rise to 5 physical Higgs bosons: h, H, A, H±

- Enhanced coupling to 3rd generation; strong coupling to down-type fermions (at large tanβ get strong enhancements to h/A/H production rates)
- Neutral φ=h/A/H produced through gg-fusion or b-associated processes

Can parameterize the masses of the Higgs bosons with two free parameters: $\tan \beta$ and $m_A$ (or $m_{H^+}$)
MSSM Neutral Higgs (h/A/H) Search

- Searching in three di-tau channels
  - 36 pb$^{-1}$ of 7 TeV collision data
  - Inclusive analysis (do not reject events based on jet multiplicity)
  - Dominant backgrounds: $Z\rightarrow\tau\tau$ (irreducible), W+jets, ttbar, $Z\rightarrow ll$, QCD

- $h/A/H\rightarrow\tau^+_1\tau^-_{HAD}$ selection criteria:
  - Single isolated lepton
  - Single hadronic tau (tau jet)
  - Oppositely charged tau and lepton
  - Missing $E_T > 20$ GeV
  - Transverse mass requirement to reject W bosons ($M_T < 30$ GeV)
  - Discriminating variable: visible mass

$$M_T = \sqrt{2p_T^e/\mu E_T^{miss}(1 - \cos \Delta\phi)}$$
MSSM Neutral Higgs (h/A/H) Search

- Background estimation using data-driven techniques
- $Z\rightarrow\tau\tau$ from MC cross-checked using embedding:
  - Select $Z\rightarrow\mu\mu$ events in data
  - Replace $\mu$ with $\tau$ from simulation

- QCD multi-jet and W+jets:
  - Assume that the QCD visible mass shape is the same for the opposite-sign (OS) and same-sign (SS) events (an assumption verified using simulated events)
  - Background estimated from the SS data sample.
  - Correction factor needed for $W+$jets $n_{OS-SS}$ taken from data control region; shape from MC

- Dominant systematic uncertainties:
  - Experimental: jet and tau energy scale (signal 19%; $Z\rightarrow\tau\tau$ 30%)
  - Theoretical: cross section (signal 14%; $Z\rightarrow\tau\tau$ 5%)
MSSM Neutral Higgs (h/A/H) Search

- **h/A/H→τ_e-τ_μ** selection criteria:
  - Single electron trigger
  - One e (p_T>20 GeV) and μ (p_T>10 GeV); opposite charge; isolated
  - p_T(e) + p_T(μ) + MET < 120 GeV
  - Δϕ(e, μ) > 2 rad (e.g., ttbar, single top and di-boson suppression)
  - Discriminating variable: effective mass

- **Backgrounds:**
  - Z→ττ estimated from MC and shape validated using the embedding method
  - Multi-jet estimated from data using ABCD method (iso. and OS/SS)

- **Systematics**
  - MC background cross-sections (5-10%), multi-jet estimate (~20%)

<table>
<thead>
<tr>
<th>Final state</th>
<th>Exp. Background</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>eμ</td>
<td>63 ± 7</td>
<td>70</td>
</tr>
<tr>
<td>lτ_had</td>
<td>206 ± 35</td>
<td>206</td>
</tr>
<tr>
<td>Sum</td>
<td>269 ± 36</td>
<td>276</td>
</tr>
</tbody>
</table>
MSSM Neutral Higgs (h/A/H) Search

- Combine the $T_e$-$T_{HAD}$, $T_\mu$-$T_{HAD}$ and $T_e$-$T_\mu$ channels
- Exclusion limit calculated using a shape analysis with the visible and effective mass distributions with a profile likelihood approach
  - Limit with the $m_h^{\text{max}}$ benchmark scenario
A Generic 2HDM: Charged Higgs Bosons

- Charged Higgs bosons could be produced from a generic 2HDM
- $H^+$ Production:
  - Light $H^+$: $pp \rightarrow tt \rightarrow bW bH^+$
  - Heavy $H^+$: $gb \rightarrow tH^+$
- $H^+$ Decay:
  - Light $H^+$: Almost exclusively to $\tau\nu$
  - Heavy $H^+$: $tb; \tau\nu; \chi^+\chi^0$

<table>
<thead>
<tr>
<th>Production</th>
<th>$H^+$ Decay</th>
<th>W Decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp\rightarrow tt, t\rightarrow bH^+$</td>
<td>$\tau_H\nu$</td>
<td>$qq$</td>
</tr>
<tr>
<td>$pp\rightarrow tt, t\rightarrow bH^+$</td>
<td>$\tau_H\nu$</td>
<td>$lv$</td>
</tr>
<tr>
<td>$pp\rightarrow tt, t\rightarrow bH^+$</td>
<td>$\tau_L\nu$</td>
<td>$qq$</td>
</tr>
<tr>
<td>$pp\rightarrow tt, t\rightarrow bH^+$</td>
<td>$\tau_L\nu$</td>
<td>$lv$</td>
</tr>
<tr>
<td>$pp\rightarrow tt, t\rightarrow bH^+$</td>
<td>$cs$</td>
<td>$lv$</td>
</tr>
<tr>
<td>$gb\rightarrow tH^+$</td>
<td>$tb$</td>
<td>$qq, lv$</td>
</tr>
<tr>
<td>$gb\rightarrow tH^+$</td>
<td>$\tau_H\nu$</td>
<td>$qq$</td>
</tr>
</tbody>
</table>
Charged Higgs: $H^+ \rightarrow \tau(\text{had})\nu$

- Each of the backgrounds are determined in a data-driven way:
  - $e \rightarrow \tau$ fakes using tag-and-probe method with $Z \rightarrow ee$ in 7 TeV collision data
  - jet $\rightarrow \tau$ fakes using $\gamma + $jet events from data
  - QCD by inverting the tau selection to obtain a control sample in data
  - True $\tau$ backgrounds using an embedding method on $t\bar{t}$bar data events with muons (with the exception of the $\tau$+lepton final state)

- Reasonably good agreement with data in our final discriminating vars.
- Working on $H^+$ searches in these final states with $>1$ fb$^{-1}$ of data now
Charged Higgs: $H^+ \rightarrow \tau^{\pm}(\text{lep})\nu$

- As a first step, used 2010 data to test our data-driven background estimates and discriminating variables that had been recently introduced.
- Reasonably good agreement with data in our final discriminating vars.
- Working on $H^+$ searches in these final states with $>1$ fb$^{-1}$ of data now.

**dilepton analysis**

**lepton+jets analysis**

Generalized transverse mass,
Charged Higgs: $H^+ \rightarrow c\bar{s}$

- Final state allows for full reconstruction of the $H^+$ candidates

- Selection criteria:
  - Isolated lepton
  - MET requirement
  - $\geq 4$ jets
  - $\geq 1$ b-tag
  - $m_T$ requirement
  - Entire event reconstructed using a $\chi^2$ fitter

\[
\chi^2 = \sum_{i=l,4\text{ jets}} \frac{(p_T^{i,\text{fit}} - p_T^{i,\text{meas}})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_{j,\text{UE,fit}} - p_{j,\text{UE,meas}})^2}{\sigma_{\text{UE}}^2} + \sum_{k=b,j,blv} \frac{(M_k - M_{\text{top}})^2}{\sigma_{\text{top}}^2}.
\]
Charged Higgs: $H^+ \rightarrow c\bar{s}$

- Examine the di-jet spectrum from ttbar events and look for a second peak
  - After selection, ttbar background > 80%
  - Data-driven estimate for QCD
  - Number of events observed agrees with SM expectation

### Channel

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

### $\mathcal{B}(t \rightarrow H^+ b) = 10\%$

- $t\bar{t} \rightarrow H^+ b W^- \bar{b}$: $20^{+3}_{-4}$
- $t\bar{t} \rightarrow W^+ b W^- \bar{b}$: $127^{+19}_{-23}$

### Limits at 95% CL

- Expected Limit
- Expected $\pm 1\sigma$
- Expected $\pm 2\sigma$
- Observed Limit
- CDF Observed
- D0 Observed
Conclusion

- The LHC era has begun!
  - Proton-proton collisions at world-record energies last year
  - ATLAS collected nearly 50 pb\(^{-1}\) of data in 2010
  - For 2011 ATLAS has collected >1.5 fb\(^{-1}\) thus far

- First ATLAS limits with ~40 pb\(^{-1}\) on
  - MSSM h/A/H \(\rightarrow\) \(\tau\tau\)
  - MSSM \(H^\pm\) \(\rightarrow\) cs

- Expected exclusion limits with ~1 - 2 fb\(^{-1}\) look very promising for BSM Higgs boson searches

- Or perhaps something even more exciting if Nature is kind...
Back-up Slides
Calculated using HIGLU and ggh@nnlo
For bbh a matching scheme has been implemented to combine 4 (NLO QCD) and 5-flavor (NNLO QCD) calculations
4-flavor cross-sections are known to be more conservative (underestimates the cross-section for large Higgs boson masses)
Error bands of both the 4FS and 5FS overlap at low masses
“Santander matching” gives equal weight to both calculations at $M_H=100$ GeV and about 1/3 4FS and 2/3 5FS at $M_H=300$ GeV
MSSM Neutral Higgs (h/A/H) Search

- Limits for individual channels
Charged Higgs: $\tau+$jets channel

Event selection criteria:

1. Event preselection:
   (a) Event-level cleaning cuts.
   (b) $E_T^{\text{miss}}$ plus $\tau$-trigger.
   (c) At least 4 jets with $p_T > 20$ GeV.

2. Exactly one $\tau$ jet with $p_T > 20$ GeV. ("tight" LLH)

3. Veto identified electrons and muons.

4. $E_T^{\text{miss}} > 20$ GeV.

5. $E_T^{\text{miss}} / \sqrt{\sum E_T} > 3$ GeV$^{1/2}$.

6. At least one $b$-tagged jet.

7. The $jjb$ candidate with the highest $p_T^{jjb}$ value must satisfy $m(jjb) \in [120, 240]$ GeV.
Charged Higgs: $\tau$+lepton channel

- Event selection criteria:

1. Event preselection:
   (a) Event-level cleaning cuts.
   (b) Lepton trigger.
   (c) Exactly one trigger-matched isolated lepton with $p_T > 20$ GeV.

2. Exactly one $\tau$ jet with $p_T > 20$ GeV. ("tight" LLH)

3. At least two jets with $p_T > 20$ GeV.

4. At least one of the jets is $b$-tagged.

5. $E_T^{\text{miss}} > 60$ GeV.

6. $\sum E_T > 200$ GeV.

7. Selected $\tau$ jet and lepton have opposite charge.
Hadronic Tau Reconstruction in ATLAS

• **Reconstruction seed jets**
  - Calorimeter jets reconstructed with the anti-kT algorithm (starting from topological clusters)
  - Distance parameter $R = 0.4$

• **Track Association**
  - A track is associated with tau candidate if it is within the core cone ($\Delta R < 0.2$ of the seed jet axis)
  - Also pass the following criteria:
    • $p_T > 1$ GeV
    • At least 7 hits in the silicon tracker (B-layer $\geq 1$, pixel $\geq 2$)
    • Requirements on transverse and longitudinal impact parameters ($|d_0| < 1.0$ mm and $|z_0 \sin \theta| < 1.5$ mm)

• But, hadronic tau reconstruction alone is not enough...
Hadronic Tau Identification in ATLAS

- Use discriminating variables that give us the upper hand

\[
R_{\text{track}} = \frac{\sum_{i} \Delta R_i < 0.4 \ p_T, \ i}{\sum_{i} \Delta R_i < 0.4 \ p_T, i}
\]
Track Radius

\[
f_{\text{track}} = \frac{p_{T,1}^{\text{track}}}{p_T}
\]
Leading Track Momentum Fraction

\[
R_{\text{EM}} = \frac{\sum_{i\in\{\text{EM 0-2}\}} \Delta R_i < 0.4 \ E_{\text{T},i}^{\text{EM}}}{\sum_{i\in\{\text{EM 0-2}\}} \Delta R_i < 0.4 \ E_{\text{T},i}^{\text{EM}}}
\]
Electromagnetic Radius

\[
f_{\text{core}} = \frac{\sum_{i\in\{\text{all}\}} \ E_{\text{T},i}^{\text{EM}}}{\sum_{i\in\{\text{all}\}} \ E_{\text{T},i}^{\text{EM}}}
\]
Core Energy Fraction

\[
S_T = \frac{L_T^{\text{flight}}}{\delta L_T^{\text{flight}}}
\]
Transverse Flight Path Significance

\[
S_T = \frac{E_{\text{T}}^{\text{flight}}}{\delta E_T^{\text{flight}}}
\]
Electromagnetic Fraction

\[
f_{\text{track}} = \frac{p_{T,1}^{\text{track}}}{p_T}
\]
Leading Track Momentum Fraction

\[
R_{\text{EM}} = \frac{\sum_{i\in\{\text{EM 0-2}\}} \Delta R_i < 0.4 \ E_{\text{T},i}^{\text{EM}}}{\sum_{i\in\{\text{EM 0-2}\}} \Delta R_i < 0.4 \ E_{\text{T},i}^{\text{EM}}}
\]
Electromagnetic Radius

ATLAS Preliminary
3 prongs 15 GeV < p_T < 60 GeV
- 2010 dijet data \(\int dt L = 23 \text{ pb}^{-1}\)

ATLAS-CONF-2011-077
To distinguish between tau leptons and jets, investigated three independent identification algorithms:

- Simple cut-based, projective likelihood (LLH), and Boosted Decision Tree (BDT)
- Cut-based ID uses a subset of the discriminating variables
- Trained separately based on number of prongs
- Distinction between an electron and tau is made using an electron veto
- Tau ID tuned for signal efficiencies of ~30% (tight) and ~60% (loose)

Background efficiency measured using collision data
- Used 7 TeV collision data collected late in 2010
- Background sample taken from di-jet events

\[
\varepsilon_{\text{sig}} = \frac{N_{\tau}^{\text{pass,match}}}{N_{\tau}^{\text{match}}}
\]

\[
\varepsilon_{\text{bkgd}} = \frac{N_{\text{bkgd}}^{\text{pass}}}{N_{\text{bkgd}}^{\text{total}}}
\]
The NMSSM: $\mu\mu$ channel

- The Next-to-MSSM
  - Introduces a complex singlet scalar field
  - Higgs sector expands as a result:
    - 3 CP-even scalars: $h_1, h_2, h_3$
    - 2 CP-odd scalars: $a_1, a_2$
    - 2 Charged scalars: $H^\pm$

- The light CP-odd Higgs, $a_1$
  - Could be very light, e.g. $\sim 10$ GeV
  - Could have dominant production mode $h \rightarrow a_1 a_1$

- In the ideal scenario
  - $m_{a_1} < 2 m_B$
  - Dominant decay modes into $\tau\tau, c\bar{c}, g\bar{g}$
  - $\mu\mu$ final state is a clean search channel

Plots from arXiv:0911.2460v5
The NMSSM: $a_1 \rightarrow \mu \mu$ channel

- Event selection criteria:
  - $\geq 2\mu$ with $p_T > 4$ GeV; $|\eta| < 2.5$
  - Oppositely-charged muon pairs in the range $4.5 < m_{\mu\mu} < 14$ GeV are analyzed using a likelihood ratio

- Use a Likelihood Ratio:
  - Use di-muon vertex fit quality and isolation
  - Signal PDFs taken from $\Upsilon(1S)$; background subtracted from sidebands: $6 < m_{\mu\mu} < 7.5$ GeV and $11.5 < m_{\mu\mu} < 12$ GeV
  - Background estimated from sidebands: $4.5 < m_{\mu\mu} < 5.5$ GeV and $12.5 < m_{\mu\mu} < 14$ GeV

- Limits:
  - Likelihood function with 50 MeV bins
  - Separate fits in the regions 6-11 GeV and 9-12 GeV

- ATLAS-CONF-2011-020