Searches for Beyond-Standard Model Higgs boson

Ohad Silbert

Weizmann Institute of Science, Rehovot, Israel

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On Behalf of the ATLAS Collaboration
Neutral Higgs Searches

- Fermiophobic Higgs
- MSSM $A/H/h \rightarrow \tau^+ \tau^-$
- SM4 Interpretation
  will not be covered here.
  ATLAS-CONF-2011-135. 1.0 – 2.3 fb$^{-1}$

- $h \rightarrow$ long lived particles
  will not be covered here.
  arXiv:1203.1303 [hep-ex]. 1.94 fb$^{-1}$

- nMSSM $a_1 \rightarrow \mu^+ \mu^-$
  will not be covered here.
  ATLAS-CONF-2011-020. 39.3 pb$^{-1}$

Charged Higgs Searches

- $H^{\pm} \rightarrow \tau^{\pm} \nu$
- $H^{\pm} \rightarrow cs$
  will not be covered here.
  ATLAS-CONF-2011-094. 35 pb$^{-1}$

Doubly Charged Higgs Searches

- $H^{\pm\pm} \rightarrow \mu^{\pm} \mu^{\pm}$
Fermiophobic Higgs


Fermiophobic Benchmark Scenario

- Suppressed coupling of the Higgs to fermions (e.g. 2DHM, triplet models)

Benchmark Scenario

- Couplings to fermions are set to zero
- Coupling to gauge bosons are set to SM values

Channels

- Gluon fusion production is suppressed ⇒ boosted Higgs from VH and VBF
- $\sigma \times BR(H \rightarrow \gamma\gamma)$ is enhanced for $m_H < 120$ GeV

Graph showing cross-section and branching ratios for various Higgs decay channels at $\sqrt{s} = 7$ TeV.
Fermiophobic Higgs

- Same selection as SM $H \rightarrow \gamma\gamma$
- 2 isolated photons
  $p_T > 40/20$ GeV
  $100 < m_{\gamma\gamma} < 160$ GeV
- 9 analysis categories based on:
  photon impact point in calorimeter
  photon conversion
  low/high $p_T$ relative to 40 GeV
- Signal model: Crystal-Ball + Gaussian
- Background model: exponential

\[ \text{ATLAS simulation} \]
\[ m_H = 120 \text{ GeV} \]
\[ \text{FWHM} = 3.7 \text{ GeV} \]
\[ \sigma_{CB} = 1.6 \text{ GeV} \]
\[ \text{High } p_T \text{ categories} \]

\[ \text{ATLAS} \]
\[ \text{Data 2011} \]
\[ \text{Low } p_T \text{ categories + converted transition} \]
\[ m_H = 120 \text{ GeV (MC)} \]
\[ \sqrt{s} = 7 \text{ TeV}, \int L dt = 4.9 \text{ fb}^{-1} \]

\[ \text{ATLAS} \]
\[ \text{High } p_T \text{ categories} \]
\[ m_H = 120 \text{ GeV (MC)} \]
\[ \sqrt{s} = 7 \text{ TeV}, \int L dt = 4.9 \text{ fb}^{-1} \]
Fermiophobic Higgs: Limits

- Observed exclusion (95% CL):
  \(110.0 - 118.0\) GeV
  \(119.5 - 121.0\) GeV

- Expected exclusion (95% CL):
  \(110.0 - 123.5\) GeV

Expected limit on \(\sigma/\sigma_0\):
- Observed CL\(_S\) limit
- Expected CL\(_S\) limit

Observed largest excess at \(m_H = 125.5\) GeV
- local: 2.9\(\sigma\)
- global: 1.6\(\sigma\)

Diagram showing the limits on \(m_H\) and \(\sigma/\sigma_0\) with observed and expected values.
MSSM $A/H/h \rightarrow \tau^+\tau^-$

ATLAS-CONF-2011-132. (1.06 fb$^{-1}$)

MSSM Higgs sector

- 2 Higgs doublets
  - light and heavy scalars: $h, H$
  - pseudo-scalar: $A$
  - charged: $H^\pm$

- $m_h^{max}$ benchmark scenario
  - free parameters $m_A$, $\tan\beta$

- for high $\tan\beta$
  - coupling to down-type fermions enhanced
  - coupling to gauge bosons suppressed
  - $\text{BR}(\Phi \rightarrow \tau\tau) \approx 10\%$

- Search for the collective signature of $h, H$ and $A$

Tag unique signature of hadronic taus:
- narrow, collimated jet
- isolated energy deposit and tracks
- large EM component
- track multiplicity 1 or 3 high leading track momentum fraction

Efficiency: $\sim 60\%$
Missidentification rate: $\sim 5\%$

$	ext{BR}(\Phi \rightarrow \tau\tau)$

0.1% others

$\pi^\pm + n\pi^0$

49.5%

$\pi^\mp$

17.4%

$\pi^0$

15.2%

$\mu^e$

17.8%

$\pi^\pm$ + $n\pi^0$

$\pi^\mp$ + $n\pi^0$

$\tau$ decay
### MSSM $A/H/h \rightarrow \tau^+\tau^-$: Event selection

<table>
<thead>
<tr>
<th>electron-muon</th>
<th>lepton-hadron</th>
<th>hadron-hadron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opposite sign, isolated, high $p_T$ $e\mu$ pair</td>
<td>Opposite sign, isolated, high $p_T$ $\ell\tau_{had}$ pair</td>
<td>di-$\tau_{had}$ trigger</td>
</tr>
<tr>
<td>$p_T^e + p_T^\mu + \not{E}_T &lt; 120$ GeV</td>
<td>$\not{E}_T &gt; 20$ GeV</td>
<td>Opposite sign di-$\tau_{had}$</td>
</tr>
<tr>
<td>$\Delta \phi_{e\mu} &gt; 2$</td>
<td>$m_T^W &lt; 30$ GeV</td>
<td>$p_T &gt; 45/30$ GeV</td>
</tr>
</tbody>
</table>

$m_{\tau\tau}^{\text{eff}} = \sqrt{(p_e + p_\mu + p_{\not{E}_T})^2}$

Maximum probability $m_{\tau\tau} (\text{MMC})$

$m_{\text{vis}} = \sqrt{(p_{\tau_{had1}} + p_{\tau_{had2}})^2}$

<table>
<thead>
<tr>
<th>electron-muon channel</th>
<th>lepton-hadron channel</th>
<th>hadron-hadron channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data 2011</td>
<td>Data 2011</td>
<td>Data 2011</td>
</tr>
<tr>
<td>$A(120)/h/H \rightarrow \tau \tau$, $\tan\beta=20$</td>
<td>$Z/\gamma(\rightarrow\tau\tau)$ embedded</td>
<td>$A(200)/H/h \rightarrow \tau \tau$, $\tan\beta=20$</td>
</tr>
<tr>
<td>$Z/\gamma(\rightarrow\tau\tau)$ embedded</td>
<td>Others (OS-SS)</td>
<td>$Z/\gamma(\rightarrow\tau\tau)$</td>
</tr>
<tr>
<td>Diboson</td>
<td>W+jets (OS-SS)</td>
<td>Others</td>
</tr>
<tr>
<td>QCD multi-jet</td>
<td>Same Sign</td>
<td>Others</td>
</tr>
<tr>
<td>$\ell&amp;$ single-$t$ syst.</td>
<td>stat.</td>
<td>stat.</td>
</tr>
</tbody>
</table>

$\sqrt{s} = 7$ TeV, $\int L = 1.06$ fb$^{-1}$

**ATLAS** Preliminary
MSSM $A/H/h \to \tau^+\tau^-$: Embedding

### Model $Z/\gamma^* \to \tau\tau$

- $e\mu \sim 90$
- $\ell\tau_{\text{had}} \sim 70$
- $\tau_{\text{had}}\tau_{\text{had}} \sim 20$

1. Measure high $p_T$ di-$\mu$, $m_{\mu\mu} > 40$ GeV
2. Remove muon hits
3. Simulate Tau decay
4. Normalize to MC

### Model $W \to \tau\nu$

- $\tau_{\text{had}}\tau_{\text{had}} \sim 10$

1. Measure high $p_T$ muons, $m_W > 40$ GeV
2. Remove muon hits
3. Simulate Tau decay
4. Normalize to MC

Note - Embedding procedure in the $\tau_{\text{had}}\tau_{\text{had}}$ is a cross check for MC
MSSM $A/H/h \rightarrow \tau^+\tau^-$: Exclusion plots

Exclusion @ 95% CL
Exist in non-minimal Higgs scenarios (e.g. 2DHM, Higgs triplet models)

production and decay:

\[ m_{H^\pm} < m_t \Rightarrow t \rightarrow bH^+ \]
\[ \tan \beta > 2 \Rightarrow H^+ \rightarrow \tau \nu \text{ dominant} \]

heavy \( H^\pm \):

\[ m_{H^\pm} < m_t \Rightarrow gb \rightarrow tH^+ \]

more data is needed

Search channels

\[ t\bar{t} \rightarrow b\bar{b}H^\pm W^\mp \rightarrow b\bar{b}(\tau\ell\nu)(q\bar{q}) \]
\[ t\bar{t} \rightarrow b\bar{b}H^\pm W^\mp \rightarrow b\bar{b}(\tau_{had}\nu)(q\bar{q}) \]
\[ t\bar{t} \rightarrow b\bar{b}H^\pm W^\mp \rightarrow b\bar{b}(\tau_{had}\nu)(q\bar{q}) \]
$H^\pm \rightarrow \tau^\pm \nu$: Event selection

Selection in $H^\pm \rightarrow \tau^\pm \nu$

- 1 isolated high $p_T$ lepton
- 4 or more high $p_T$ jets
- 2 b-tag
- $|\phi_{\ell,\text{miss}}| \geq \pi/6 \Rightarrow E_T > 40$ GeV
- $|\phi_{\ell,\text{miss}}| < \pi/6 \Rightarrow E_T |\sin (\phi_{\ell,\text{miss}})| > 20$ GeV
- event kinematics consistent with signal topology
- $\cos \theta^*_\ell < -0.6$ (normalize $t\bar{t}$ at $\cos \theta^*_\ell > -0.2$)
- $m_W^T < 60$ GeV

$$\cos \theta^*_\ell = \frac{2m^2_{b\ell}}{m^2_t - m^2_W} - 1 \approx \frac{4p^b \cdot p^\ell_T}{m^2_t - m^2_W} - 1$$

$$\left( m^T_H \right)^2 = \left( \sqrt{m^2_t + \left( \vec{p}_T^\ell + \vec{p}_T^b + \vec{p}_T^{\nu} \right)^2 - \vec{p}_T^b} \right)^2 - \left( \vec{p}_T^\ell + \vec{p}_T^{\nu} \right)^2$$
$H^\pm \rightarrow \tau^\pm \nu$ : Event selection

Selection in lepton + $H^\pm \rightarrow \tau_{had}\nu$

- isolated, opposite sign, high $p_T$ $\ell\tau_{had}$ pair
- ≥ 2 high $p_T$ jets
- at least 1 b-tag
- large $p_T$ carried by tracks from primary vertex

$E_T$ as discriminating variable

Selection in jets + $H^\pm \rightarrow \tau_{had}\nu$

- high $p_T$ $\tau_{had}$ and $E_T$
- ≥ 4 high $p_T$ jets (non tau)
- at least 1 b-tag
- lepton veto
- large $E_T$ significance
- jet kinematics consistent with signal topology

Transverse mass as discriminating variable

$$m_T = \sqrt{2p_T E_T (1 - \cos \phi_{\tau,\text{miss}})}$$
H\(^{\pm}\) → \(\tau^{\pm}\nu\): Limits

Exclusion @ 95% CL
$H^{\pm\pm} \rightarrow \mu^\pm \mu^\pm$

Phys. Rev. D 85 (2012) 032004 (1.6 fb$^{-1}$)

- Exist in left-right symmetric models, Higgs triplet and little higgs models
- dominant production $pp \rightarrow H^{++} H^{--}$
- Inclusive search for same-sign muons
- background
  - prompt muons (di-boson - MC)
  - non-prompt muons (control region)

No excess was observed
- Set limit assume production mechanism $pp \rightarrow Z/\gamma^* \rightarrow H^{++} H^{--}$

$$\sigma(pp \rightarrow H^{\pm\pm} \rightarrow \mu^\pm \mu^\pm) \leq 100\% \quad \text{Expected}$$

$$\sigma(pp \rightarrow H^{\pm\pm} \rightarrow \mu^\pm \mu^\pm) \leq 33\%$$

$$H_R(\text{GeV}) < 251 \quad H_L(\text{GeV}) < 209$$

$$H_R(\text{GeV}) < 355 \quad H_L(\text{GeV}) < 244$$
Many BSM higgs models were considered
(Still) no deviation from SM was observed
Strict upper limits were placed
New data is coming, stay tuned