BSM Higgs Boson Searches with ATLAS

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on behalf of the ATLAS collaboration
Closing in on the SM Higgs Boson

see Ralf Bernhard’s talk
Closing in on the SM Higgs Boson

Really?

see Ralf Bernhard’s talk
What if...

- ... the Higgs-boson couplings are different from the SM ones?
- ... this is only one of several SUSY (MSSM) Higgs bosons?
- ... an even more complex Higgs sector is realized in nature?
What if...

- ... the Higgs-boson couplings are different from the SM ones?
- ... this is only one of several SUSY (MSSM) Higgs bosons?
- ... an even more complex Higgs sector is realized in nature?

- Fermiophobic Higgs
- MSSM neutral Higgs
- Charged Higgs $H^+$
- Doubly charged $H^{++}$
Fermiophobic Higgs
Decreased coupling to some or all fermions in Higgs doublet and triplet models

Here: simple benchmark scenario without any Higgs-fermion coupling and SM coupling to gauge bosons

Production via Vector-Boson Fusion and associated VH production

Decays to $\gamma\gamma$, WW, ZZ, $Z\gamma$

Here: focus on $\gamma\gamma$ (enhanced w.r.t. SM for light(!) Higgs)
select events with **2 isolated photons** with $p_T > 40/25$ GeV

di-photon mass:
$100 \text{ GeV} < m_{\gamma\gamma} < 160 \text{ GeV}$

9 **analysis categories** based on

- presence of $\gamma$ conversions
- $\gamma$ calorimeter **impact point**
- $p_{Tt}$: di-photon transverse momentum orthogonal to the di-photon thrust axis in the transverse plane

**signal** $m_{\gamma\gamma}$ model:
“Crystal Ball” + wide Gaussian

**background** $m_{\gamma\gamma}$ model:
exponential

```plaintext

low $p_{Tt}$

high $p_{Tt}$

```
**Fermiophobic $H \rightarrow \gamma\gamma$ : Exclusion Limits**

- **observed** $m_H$ exclusion: $[110.0, 118.0]$, $[119.5, 121.0]$
- **expected** $m_H$ exclusion: $[110.0, 123.5]$

ATLAS-CONF-2012-013 (4.9 fb$^{-1}$)

ATLAS Preliminary

Data 2011, $\sqrt{s} = 7$ TeV

$\int L dt = 4.9$ fb$^{-1}$

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ATLAS-CONF-2012-013 (4.9 fb$^{-1}$)

- **largest excess** from BG-only hypothesis at $m_H = 125.5$ GeV
- $1.6\sigma$ (with look-elsewhere)
Neutral Higgs
**MSSM**: minimal supersymmetric extension of SM

- requires 2 Higgs doublets
- → 5 Higgs bosons: $\Phi = h, H^0, A ; H^+, H^-$

- number of parameters can be reduced with additional assumptions, e.g. to $m_A, \tan\beta$

- enhanced couplings to b and tau in large regions of the parameter space (in particular high tan$\beta$)
hadronic tau decays:
- narrow, collimated jet
- isolated energy deposits and tracks
- large electromagnetic component
- low track multiplicity (1 or 3)
- high leading-track momentum fraction

multivariate identification
**MSSM Higgs → ττ : Selection**

**electron-muon**
- 1 isolated e with \( p_T > 25 \) GeV
- 1 isolated \( \mu \) with \( p_T > 20 \) GeV
- opposite charges
- \((\text{sum of lepton } p_T \text{ and } E_{T\text{miss}}) < 120 \text{ GeV, } \Delta \Phi_{e,\mu} > 2.0 \text{ GeV} \) \((\top, \WW, \ZZ)\)

**lepton-hadron**
- isolated e / \( \mu \) with \( p_T > 25 / 20 \) GeV
- exactly one \( \tau_{\text{had}} \) with \( p_T > 20 \) GeV
- opposite charges
- dilepton veto \((Z, \top)\)
- \( E_{T\text{miss}} > 20 \text{ GeV} \) \((QCD)\)
- \( m_T < 30 \text{ GeV} \) \((W)\)

**hadron-hadron**
- 2-\( \tau_{\text{had}} \) trigger
- 2 \( \tau_{\text{had}} \) with \( p_T > 45 \text{ GeV and } p_T > 30 \text{ GeV} \)
- opposite charges
- lepton veto
- \( E_{T\text{miss}} > 25 \text{ GeV} \) \((QCD)\)

**ττ mass reconstruction**

**effective mass**

\[
m_{\tau\tau}^\text{effective} = \sqrt{(p_e + p_\mu + p_{E_{T\text{miss}}})^2},
\]

\[
p_{E_{T\text{miss}}} = (E_{T\text{miss}}, E_{T\text{miss},x}, E_{T\text{miss},y}, 0)
\]

**visible mass**

invariant mass of visible \( \tau \) decay products

**full reconstruction**

with “missing mass calculator” \((MMC)\)

\[(\text{NIM A654 (2011) 481})\]
Use mainly **data-driven methods**, e.g.

- $Z/\gamma^* \rightarrow \tau\tau$ from $\tau$-embedded $Z/\gamma^* \rightarrow \mu\mu$ data
- **QCD jet** background from same-sign-charge, low-MET, and/or anti-isolated lepton samples
- **W+jets** normalization from high-$m_T$ data sample (and/or same-sign charge sample - after correction)
MSSM Higgs → ττ: Results

**electron-muon**

**lepton-hadron**

**hadron-hadron**

<table>
<thead>
<tr>
<th>Final state</th>
<th>Exp. Background</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>eμ</td>
<td>(2.6 ± 0.2) × 10³</td>
<td>2472</td>
</tr>
<tr>
<td>ℓτ_{had}</td>
<td>(2.1 ± 0.4) × 10³</td>
<td>1913</td>
</tr>
<tr>
<td>τ_{had}τ_{had}</td>
<td>233 $^{+44}_{-28}$</td>
<td>245</td>
</tr>
<tr>
<td>Sum</td>
<td>(4.9 ± 0.6) × 10³</td>
<td>4630</td>
</tr>
</tbody>
</table>

consistent with predicted background yield+shape
MSSM Higgs → ττ: Exclusion Limits

Cross section \( \times \) BR

\[ \sqrt{s} = 7 \text{ TeV}, \int \text{Ldt} = 1.06 \text{ fb}^{-1} \]

\[ \text{ATLAS Preliminary} \]

\[ \sigma_{\text{SM}} \times \text{BR}(H_{SM} \rightarrow \tau\tau) \text{ theory} \]

\[ m_{H}^{\text{max}}, \mu > 0 \]

\[ \sqrt{s} = 7 \text{ TeV}, \int \text{Ldt} = 1.06 \text{ fb}^{-1} \]

\[ \text{ATLAS Preliminary} \]

\[ m_{A} \text{ [GeV]} \]

\[ \tan\beta - m_{A} \text{ plane} \]
Charged Higgs
considered channels:

\[
\begin{align*}
\bar{t}t &\rightarrow b\bar{b}H^{\pm}W^{\mp} \rightarrow b\bar{b}(\tau_{lep}v)(q\bar{q}) : \text{lepton + jets} \\
\bar{t}t &\rightarrow b\bar{b}H^{\pm}W^{\mp} \rightarrow b\bar{b}(\tau_{had}v)(\ell v) : \text{tau + lepton} \\
\bar{t}t &\rightarrow b\bar{b}H^{\pm}W^{\mp} \rightarrow b\bar{b}(\tau_{had}v)(q\bar{q}) : \text{tau + jets}
\end{align*}
\]
selection:

- 1 electron or 1 muon with $p_T > 25$ GeV / $p_T > 20$ GeV
- at least 4 jets (2 of them b-tagged) with $p_T > 20$ GeV
- $E_T^{\text{miss}} > 40$ GeV (>20 GeV for small $\phi_{l,\text{miss}}$)
- event kinematics consistent with signal topology

discriminating variables:

$$\cos \theta^*_t = \frac{2m_{bl}^2}{m_{top}^2 - m_W^2} - 1 \approx \frac{4p^b \cdot p^l}{m_{top}^2 - m_W^2} - 1$$

related to invariant mass of b jet and lepton from same top decay

$$(m_T^H)^2 = \left(\sqrt{m_{top}^2 + (p_T^l + p_T^b + p_T^{\text{miss}})^2} - p_T^b\right)^2 - (p_T^l + p_T^{\text{miss}})^2$$

lower bound on charged (W or H) boson mass from top decay
selection:
- 1 electron or 1 muon with $p_T > 25$ GeV / $p_T > 20$ GeV
- 1 hadronic tau decay with $p_T > 20$ GeV
- opposite charge
- at least 2 jets (1 of them b-tagged) with $p_T > 20$ GeV
- sum of primary-vertex track $p_T$: $\Sigma p_T > 100$ GeV

discriminating variable:
- $E_{T\text{miss}}$
**Charged Higgs: Tau + Jets**

**selection:**
- **Tau + $E_T^{\text{miss}}$ trigger**
- 1 hadronic tau decay with $p_T > 40$ GeV
- $E_T^{\text{miss}} > 65$ GeV

\[
\frac{E_{T,\text{miss}}}{0.5 \cdot \sqrt{\sum p_T}} > 13 \text{ GeV}^{1/2}
\]

- jet kinematics **consistent** with signal topology

**discriminating variable:**
- transverse mass $m_T$
Charged Higgs: Exclusion Limits

**lepton+jets**

**tau+lepton**

**tau+jets**

**combined**

ATLAS Preliminary

- Observed CLs
- Expected

\[ s = 7 \text{ TeV} \]

\[ L_{\text{int}} = 4.6 \text{ fb}^{-1} \]

J. Krosseberg                  BSM Higgs Searches with ATLAS         Moriond QCD 2012

ATLAS-CONF-2012-011 (4.6 fb\(^{-1}\))
Charged Higgs: Exclusion Limits

**lepton+jets**

- Observed CLs
- Expected
- $\pm 1\sigma$
- $\pm 2\sigma$
- Observed, $\pm 1\sigma$
- theor. uncertainties

**tau+lepton**

- Observed CLs
- Expected
- $\pm 1\sigma$
- $\pm 2\sigma$
- Observed, $\pm 1\sigma$
- theor. uncertainties

**tau+jets**

- Observed CLs
- Expected
- $\pm 1\sigma$
- $\pm 2\sigma$
- Observed, $\pm 1\sigma$
- theor. uncertainties

**combined**

- Observed CLs
- Expected
- $\pm 1\sigma$
- $\pm 2\sigma$
- Observed, $\pm 1\sigma$
- theor. uncertainties

$I_{\text{data}} = 4.6 \text{ fb}^{-1}$

$m_{H^+}^\text{max} \, \sqrt{s} = 7 \text{ TeV}$

Data 2011
Doubly-Charged Higgs
relevant in **Higgs Triplet**, **Little Higgs**, and **Left-Right Symmetric models**

- select pairs of 2 same-sign-charge muons with $p_T > 20$ GeV
- look for resonance in di-muon mass spectrum
- no significant excess over background-only prediction found
$H^{±±} \rightarrow \mu^+\mu^- :$ Exclusion Limits

Right-handed Higgs mass < 251 GeV
Left-handed Higgs mass < 355 GeV
@95% CL if $\text{Br}(H^{±±} \rightarrow \mu^+\mu^-)=100\%$

$\sigma(pp \rightarrow H^{±±}) \times \text{BR}(H^{±±} \rightarrow \mu^+\mu^-) \times [fb]$
Also... [not in this talk]

- $H^+ \rightarrow c\bar{s}$  
  ATLAS-CONF-2011-094 (35 pb$^{-1}$)

- $n$MSSM $a_1 \rightarrow \mu\mu$  
  ATLAS-CONF-2011-020 (40 pb$^{-1}$)
a number of BSM Higgs scenarios are being probed in parallel to the SM Higgs search
no indication for a BSM Higgs boson yet
searches continue with more data and improved methods
still significant room for BSM Higgs discoveries for the year ahead
Backup Material
Fermiophobic Higgs

ATLAS Preliminary

Observed SM $CL_s$ limit
- Expected SM $CL_s$ limit
- Observed Fermiophobic $CL_s$ limit
- Expected Fermiophobic $CL_s$ limit

Data 2011, $\sqrt{s} = 7$ TeV

95% CL limit on $\alpha_{BR}(H \rightarrow \gamma\gamma)$ [fb]

$m_H$ [GeV]
split missing $E_t$ into two vectors $p_{\text{mis}1,2}$ ($\rightarrow$ neutrinos)

**kinem. constraints**

$$E_{x}^{\text{miss}} = p_{\text{mis1}} \sin \theta_{\text{mis1}} \cos \phi_{\text{mis1}} + p_{\text{mis2}} \sin \theta_{\text{mis2}} \cos \phi_{\text{mis2}},$$

$$E_{y}^{\text{miss}} = p_{\text{mis1}} \sin \theta_{\text{mis1}} \sin \phi_{\text{mis1}} + p_{\text{mis2}} \sin \theta_{\text{mis2}} \sin \phi_{\text{mis2}},$$

$$m^{2}_{\tau} = m^{2}_{\text{mis1}} + m^{2}_{\text{vis1}} + 2 \sqrt{p^{2}_{\text{vis1}} + m^{2}_{\text{vis1}}} \sqrt{p^{2}_{\text{mis1}} + m^{2}_{\text{mis1}}} - 2 p_{\text{vis1}} p_{\text{mis1}} \cos \Delta \theta_{\text{vm1}},$$

$$m^{2}_{\tau} = m^{2}_{\text{vis2}} + 2 \sqrt{p^{2}_{\text{vis2}} + m^{2}_{\text{vis2}}} \cdot p_{\text{mis2}},$$

$$- 2 p_{\text{vis2}} p_{\text{mis2}} \cos \Delta \theta_{\text{vm2}}$$

- **scan free parameters and weight with expected probability to come from $\tau$ decay**
- **take maximum of obtained di-$\tau$ mass distribution**

A. Elagin, P. Murat, A. Pranko, A. Safonov
arXiv:1012.4686 ; NIM A654 (2011) 481
τ Embedding (e.g. for Z → ττ Modeling)

- reliable model of $Z \rightarrow ττ$ background shape essential (for low-mass Higgs)
- desirable to use real data but cannot select $Z \rightarrow ττ$ signal-free
- use $Z \rightarrow μμ$ data as starting point ($\approx$ signal-free due to small H-μ coupling)
  
- select $Z \rightarrow μμ$ data events
- remove muon tracks and nearby calorimeter cells
- simulate stand-alone $Z \rightarrow ττ$ decays such that simulated τ four-momenta are the same as original muons ones (after mass correction)
- merge into single hybrid event
- re-reconstruct objects and missing $E_t$

underlying event, pileup, hadronic activity, ... from data
Event display of a tau-mu dilepton candidate. The muon track is shown in red, the (3-prong) tau candidate is shown at the lower right in the x-y projections. The muon has positive electric charge, the tau negative. The tau candidate has multivariate discriminant values of $\text{BDT}_\tau = 0.98$ and $\text{BDT}_e = 0.86$. The analysis used to select the event is described in ATLAS-CONF-2011-119, including the explanation of these BDT variables. The b-tagged jet is indicated by the blue tracks in the vertex-region zoomed view. This jet is the leading jet in the event with a $p_T$ of 144 GeV, and an SV0 decay length significance of 22.9. The estimated signal-to-background ratio for the selection employed is above 3. Further event properties:

- $p_T(\tau_{had}) = 53$ GeV
- $p_T(\mu) = 20$ GeV
- $E_{T_{miss}} = 39$ GeV
- $N_{jet}(p_T > 25$ GeV) = 3, including the $\tau$-jet
H^{±±} → \mu^+\mu^*: Exclusion Limits

ATLAS

\int L dt = 1.6 fb^{-1}
\sqrt{s} = 7 TeV

BR(H^{±±} \rightarrow \mu^+\mu^-)

M(H^{±±}) [GeV]