Search for Higgs Bosons Beyond the Standard Model with ATLAS

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On behalf of the ATLAS Collaboration

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- Fermiophobic Higgs bosons
  \[ H \to \gamma\gamma \]

- MSSM neutral Higgs bosons
  \[ h/H/A \to \tau\tau \]

- Charged Higgs bosons:
  - \[ H^+ \to \tau_{\text{had}}\nu \]
  - \[ H^+ \to \tau_\ell\nu \]
  - \[ H^+ \to c\bar{s} \]

- Doubly charged Higgs bosons
  \[ H^{++} \to \mu^+\mu^+ \]

- NMSSM light neutral Higgs bosons
  \[ a_1 \to \mu\mu \]

New preliminary results with 4.9fb$^{-1}$

Preliminary results with 1.06fb$^{-1}$

Submitted to JHEP last week! (4.7fb$^{-1}$)

Preliminary results with 0.035fb$^{-1}$

Published in PRL (1.6fb$^{-1}$)

Preliminary results with 0.037fb$^{-1}$
2HDM and Higgs triplet models with reduced couplings to fermions. Simple benchmark scenario:
- No fermion-Higgs couplings
- SM boson-Higgs couplings

Production in VBF and associated with $W/Z$

Decay: $\gamma\gamma$, $WW$, $ZZ$, $Z\gamma$

$\sigma \times BR$ larger than SM for light Higgs bosons

Higher $p_T$ (recoil)
Selection (Identical to SM $H \rightarrow \gamma\gamma$)

- 2 isolated photons, $p_T > 40$ GeV, 25 GeV
- $100 < m_{\gamma\gamma} < 160$ GeV
- 9 categories
  - Presence of photon conversions
  - Photon calorimeter impact point
  - $p_{Tt}$, component of $p_T,\gamma\gamma \perp \gamma\gamma$-thrust axis

- $m_{\gamma\gamma}$ signal model:
  Crystal Ball + wide Gaussian(tail)

- $m_{\gamma\gamma}$ background model:
  Falling exponential
Largest excess at \( m_H = 125.5 \text{ GeV} \)

**Significance** including look-elsewhere effect: \( 1.6\sigma \)

(Or 5% prob. for a background fluctuation)

Exclusion limits at 95% confidence level using the profile likelihood method with \( \text{CL}_S \)

**Expected** \( m_H \) exclusion:
110.0 – 123.5 GeV

**Observed** \( m_H \) exclusion:
110.0 – 118.0 GeV and 119.5 – 121.0 GeV
2 Higgs-doublets → 5 Higgs bosons
\( \Phi = H, h, A, H^\pm \)

- Free parameters at tree level: \( m_A \),
  \( \tan \beta = v_u/v_d \)

- Enhanced couplings to \( b \) and \( \tau \) in large parts of the parameter space (\( \sigma_{bbA} \approx \tan^2 \beta \))

Production:
Typical signature:

- One or three charged tracks
- Collimated calorimeter energy deposits
- Large leading track momentum fraction
- Secondary vertex reconstruction
**Selection**

**e + µ:**
- 1 isolated $e$, $p_T > 22$ GeV
- 1 isolated $µ$, $p_T > 20$ GeV
- Opposite charges
- $\Delta \Phi(e, \mu) > 2$ rad
- $P_T^e + P_T^\mu + E_T^{miss} < 120$ GeV

**e/µ + $\tau_{had}$:**
- 1 isolated $e/\mu$, $p_T > 25/20$ GeV
- 1 $\tau_{had}$, $p_T > 20$ GeV
- Opposite charges
- Di-lepton veto
- $E_T^{miss} > 20$ GeV
- $m_T < 30$ GeV

**$\tau_{had} + \tau_{had}$:**
- Di-$\tau_{had}$ trigger
- 2 $\tau_{had}$, $p_T > 45/30$ GeV
- Opposite charges
- Light lepton veto
- $E_T^{miss} > 30$ GeV

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**Plots:**

1. **$e\mu$ channel**
   - Data 2011
   - $A(120)/h \rightarrow \tau\tau$, $\tan\beta=20$
   - $Z\gamma^*(\rightarrow \tau\tau)$ embedded
   - Others
   - Diboson
   - QCD multi-jet
   - If $\tau$ & single-$t$
   - syst.

2. **$e\tau_{had} + \mu\tau_{had}$ channels**
   - Data 2011
   - $A(120)/h \rightarrow \tau\tau$, $\tan\beta=20$
   - $Z\gamma^*(\rightarrow \tau\tau)$ emb.(OS-SS)
   - Others(OS-SS)
   - W+jets (OS-SS)
   - Same Sign
   - stat.

3. **$\tau_{had} + \tau_{had}$ Channel**
   - Data 2011
   - $A(200)/H \rightarrow \tau\tau$, $\tan\beta=20$
   - Multi-Jet
   - $Z\gamma^*(\rightarrow \tau\tau)$
   - $W\rightarrow \tau\nu +$ jets
   - Others
   - stat.
- Invariant mass $m_{\text{vis}}$ of visible decay products
- Effective mass: $m_{\text{eff}} = \sqrt{(p_e + p_\mu + p_{\text{miss}})^2}$, with $p_{\text{miss}} = (E_T^{\text{miss}}, E_x^{\text{miss}}, E_y^{\text{miss}}, E_z^{\text{miss}} = 0)$.
- New method called Missing Mass Calculator (MMC) (see arXiv:1012.4686)

MMC (lep-had case):
- 7 unknowns: “Missing” 3-momenta and mass of $\nu\nu$ system
- 4 constraints: $E_{T,x}^{\text{miss}}, E_{T,y}^{\text{miss}}, m_{\tau_1}, m_{\tau_2}$
  \rightarrow \text{scan } \Delta \Phi_1(\nu_\tau, h), \Delta \Phi_2(\nu_\tau, \nu_\ell, \ell), m_{\nu\nu}$
- Weight solutions according to 3D angle in solution
- Maximum of weighted $m_{\tau\tau}$ distribution is the MMC mass
Based on data control samples:

- \( Z/\gamma^* \rightarrow \tau \tau \) from "\( \tau \)-embedded" 
  \( Z/\gamma^* \rightarrow \mu \mu \) data sample
- QCD multijet backgrounds from control samples with same-sign charges and low \( E_{T\text{miss}} \) or inverted lepton isolation
- \( W + \text{jets} \) from high \( m_T(\ell, E_{T\text{miss}}) \) control region
Neutral MSSM Higgs Bosons IV

Results

\( e + \mu : \)

\( e/\mu + \tau_{\text{had}} : \)

\( \tau_{\text{had}} + \tau_{\text{had}} : \)

<table>
<thead>
<tr>
<th>Final state</th>
<th>Exp. Background</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>( e\mu )</td>
<td>((2.6 \pm 0.2) \times 10^3)</td>
<td>2472</td>
</tr>
<tr>
<td>( \ell\tau_{\text{had}} )</td>
<td>((2.1 \pm 0.4) \times 10^3)</td>
<td>1913</td>
</tr>
<tr>
<td>( \tau_{\text{had}}\tau_{\text{had}} )</td>
<td>233 ( ^{+44}_{-28} )</td>
<td>245</td>
</tr>
<tr>
<td>Sum</td>
<td>((4.9 \pm 0.6) \times 10^3)</td>
<td>4630</td>
</tr>
</tbody>
</table>
Neutral MSSM Higgs Bosons VII
Exclusion Limits (ATLAS-CONF-2011-132)

Assume only one resonance $\Phi$
- Pure $gg \rightarrow \Phi$ or pure $bb\Phi$ production

$m_A$, $\tan\beta$ plane
- Need to assume specific (c)MSSM scenario
- Here: $m_h^{max}$ scenario
Comparison of Search Channels

Update to full 4.9 fb\(^{-1}\) data set and with inclusion of b-tagging in progress!
- Predicted in Higgs doublet (e.g. MSSM) and triplet models
- \( m_{H^+} < m_t \): dominantly produced in top quark decays
- \( m_{H^+} > m_t \): \( gb \rightarrow tH^+ \) production important (more data needed)
- For \( \tan \beta > 3 \) preferred decay mode is \( H^+ \rightarrow \tau \nu \) (here: assume 100%, unless MSSM)

Channels:

- \( \bar{t}t \rightarrow b\bar{b}H^\pm W^\mp \rightarrow b\bar{b}(\tau_{lep} \nu)(q\bar{q}) \) : lepton + jets
- \( \bar{t}t \rightarrow b\bar{b}H^\pm W^\mp \rightarrow b\bar{b}(\tau_{had} \nu)(\ell \nu) \) : \( \tau_{had} + \) lepton
- \( \bar{t}t \rightarrow b\bar{b}H^\pm W^\mp \rightarrow b\bar{b}(\tau_{had} \nu)(q\bar{q}) \) : \( \tau_{had} + \) jets
1 isolated $e/\mu$, $p_T > 25/20$ GeV

$\geq 4$ jets (2 b-tagged), $p_T > 20$ GeV

$E^{\text{miss}}_T > 40$ GeV if $|\Phi_{\ell,\text{miss}}| \geq \pi/6$

$E^{\text{miss}}_T \times |\sin \Phi_{\ell,\text{miss}}| > 20$ GeV if $|\Phi_{\ell,\text{miss}}| < \pi/6$

Minimize $\chi^2 = \left( \frac{(m_{jjb}-m_{top})^2}{\sigma_{top}^2} \right) + \left( \frac{(m_{jj}-m_W)^2}{\sigma_W^2} \right)$ to get “hadronic side”

Discriminating variables:

$$\cos \Theta^*_\ell = \frac{2m_{bl}}{m_{top}^2 - m_W^2} - 1 \approx \frac{4p^b \cdot p^\ell}{m_{top}^2 - m_W^2} - 1$$

$$m_H^2 = (\sqrt{m_{top}^2 + (p_T^{\ell} + p_T^b + p_T^{\text{miss}})^2} - (p_T^{\ell} + p_T^{\text{miss}})^2)^2$$

Lower bound on charged boson $(W/H^+)$ mass

Signal region: $\cos \Theta^*_\ell < -0.6$ and $m^{E^{\text{miss}}_T}_{T,\ell} < 60$ GeV
Lepton+Jets – Channel Results

- **Dominant background:** $t\bar{t}$, simulated with MC@NLO, normalized in $-0.2 < \cos \Theta_\ell^* < 1$

- **Misidentified-lepton** background determinated from control sample with loosened lepton ID

<table>
<thead>
<tr>
<th>Sample</th>
<th>Event yield (lepton+jets)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$</td>
<td>840 ± 20 ± 150</td>
</tr>
<tr>
<td>Single top quark</td>
<td>28 ± 2 +8 ± 6</td>
</tr>
<tr>
<td>$W$+jets</td>
<td>14 ± 3 +3 ± 0</td>
</tr>
<tr>
<td>$Z$+jets</td>
<td>2.1 ± 0.7 +1.2 ± 0.4</td>
</tr>
<tr>
<td>Diboson</td>
<td>0.5 ± 0.1 ± 0.2</td>
</tr>
<tr>
<td>Misidentified leptons</td>
<td>55 ± 10 ± 20</td>
</tr>
<tr>
<td>$\Sigma$ SM</td>
<td>940 ± 22 ± 150</td>
</tr>
<tr>
<td>Data</td>
<td>933</td>
</tr>
<tr>
<td>$t \to bH^+$ (130 GeV)</td>
<td>120 ± 4 ± 25</td>
</tr>
</tbody>
</table>
17/26

\( \tau_{\text{had}} + \text{Lepton Channel – Selection} \)

- 1 \( \tau_{\text{had}} \), \( p_T > 20 \text{ GeV} \)
- 1 \( e/\mu \), \( p_T > 25/20 \text{ GeV} \), opposite charge
- \( \geq 2 \) jets, \( p_T > 20 \text{ GeV} \), including \( \geq 1 \) b-tagged jet
- \( \sum p_T^{\text{tracks}} > 100 \text{ GeV} \), for tracks associated to primary vertex

Discriminating variable: \( E_T^{\text{miss}} \)

- Misidentified taus background:
  - \( e: \approx 1\% \), jets: \( \approx 55\% \); jet\( \rightarrow \tau_{\text{had}} \) mis-ID measured with \( W+\text{jets} \)
- True tau background taken from simulation
Missing transverse energy: 39GeV

Muon, pt=20GeV

Hadronic tau decay, pt=53GeV

b-jet

2nd vertex b-jet

Run Number: 182424, Event Number: 2582762
Date: 2011-05-21 20:51:17 CEST
Charged Higgs Bosons VI

$\tau_{\text{had}} + \text{jets}$ Channel – Selection

- $\tau_{\text{had}} + E_T^{\text{miss}}$ trigger
- 1 $\tau_{\text{had}}$, $p_T > 40$ GeV
- $\geq 4$ jets, $p_T > 20$ GeV, at least one b-tagged
- Veto: $\geq 2 \tau_{\text{had}}$ and light leptons
- $E_T^{\text{miss}}$ significance: $\frac{E_T^{\text{miss}}}{0.5 \sqrt{\sum p_T}} > 13$ GeV$^{1/2}$
- $E_T^{\text{miss}} > 65$ GeV
- jjb combination (highest $p_T$ one) consistent with $m_{\text{top}}$

Discriminating variable:

$$m_T = \sqrt{2 p_T^{\tau_{\text{had}}} E_T^{\text{miss}} (1 - \cos \Delta \phi)}$$

- True-tau background estimated from $\tau$ embedded $\mu$+jets events (with $t\bar{t}$ like event topology)
Estimate multijet background by fitting $E_T^{\text{miss}}$ shapes to data in control sample with inverted $\tau$ and b ID.
Combination:

Tevatron Limits: $BR < 15 - 20\%$
Charged Higgs Bosons IX
Exclusion Limits – MSSM (arXiv:1204.2760)

Combination:
- $H^+ \rightarrow c\bar{s}$ is sizable for $\tan \beta < 1$
- Suppress multijet background by requiring large $E_T^{\text{miss}}$ and $m_T$
- Kinematic fit with W and top mass constraints to find best $H^+$ candidate
- Assume $\text{BR}(H^+ \rightarrow c\bar{s}) = 100\%$, to set limits on $\text{BR}(t \rightarrow H^+ b)$
Predicted in left-right symmetric, Higgs triplet and little Higgs models

Select same sign di-muons, $p_T > 20$ GeV

Look for resonance in di-muon mass spectrum

95% confidence limits, exclude:
Right-handed Higgs mass $< 251$ GeV
Left-handed Higgs mass $< 355$ GeV

With $\text{BR}(H^{++} \rightarrow \mu\mu) = 100\%$
NMSSM $a_1 \rightarrow \mu \mu$

(ATLAS-CONF-2011-020)

- NMSSM: additional complex singlet scalar field to solve $\mu$ problem
  - $\rightarrow$ 3 CP-even scalars ($h_1, h_2, h_3$) and 2 CP-odd scalars ($a_1, a_2$)
- $a_1$ can be very light, i.e. $m_{a_1} < 2m_b$

Selection:
- Opposite sign di-muons, $p_T^{\mu} > 4$ GeV
- Likelihood ratio selection based on $\mu^+\mu^-$ vertex $\chi^2$ and $\mu$ isolation
- Limit setting by fit to mass spectrum
Many interesting beyond SM Higgs scenarios are being probed!

- **New**: Fermiphobic $H \rightarrow \gamma\gamma$, charged Higgs $H^+ \rightarrow \tau\nu$
- MSSM neutral $h/H/A \rightarrow \tau\tau$, charged $H^+ \rightarrow c\bar{s}$,
  $H^{++} \rightarrow \mu^+\mu^+$, NMSSM $a_1 \rightarrow \mu^+\mu^-$

No indication of a signal yet...

but: lots of **limits** on cross sections and branching ratios!

The searches are being continued with **improved methods** and **new data**.

→ There’s still lots of parameter space to cover within this year and after!
Systematic uncertainties:

**Signal event yield**
- Photon reconstruction and identification: ±11%
- Effect of pileup on photon identification: ±4%
- Isolation cut efficiency: ±5%
- Trigger efficiency: ±1%
- Higgs boson cross section: ±9%
- Luminosity: ±3.9%

**Signal mass resolution**
- Calorimeter energy resolution: ±12%
- Photon energy calibration: ±6%
- Effect of pileup on energy resolution: ±3%
- Photon angular resolution: ±1%

**Signal category migration**
- Higgs boson $p_T$ modelling: ±1%
- Conversion rate: ±4.5%

**Background model**: ± (0.1 – 7.9) events

Signal Model vs. MC:

- **ATLAS** simulation
- Preliminary
- Fermiophobic $H \rightarrow \gamma \gamma$
- $m_H = 120$ GeV
- FWHM = 3.7 GeV
- $\sigma_{CB} = 1.6$ GeV

Fermiophobic and SM(arXiv:1202.1414) Limit:

- 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
2 Higgs-doublets → 5 Higgs bosons

\[ \Phi = H(CP = 1), h(CP = 1), A(CP = -1), H^\pm \]

Free parameters at tree level: \( m_A, \tan \beta = \frac{v_u}{v_d} \)

Fixed mass relations at tree level:

\[
m_{H,h}^2 = \frac{1}{2} \left( m_A^2 + m_Z^2 \pm \sqrt{(m_A^2 + m_Z^2)^2 - 4m_Z^2m_A^2 \cos^2 2\beta} \right)
\]

\[
m_h^2 \leq m_Z^2 \cos^2 2\beta \leq m_Z^2
\]

Upper mass bound modified by radiative corrections (depending on SUSY parameters)

Benchmark scenarios (everything fixed but \( m_A, \tan \beta \):

- \( m_h^{\text{max}} \): \( m_h < 133 \text{ GeV} \), maximum allowed mass for \( h \)
- Nomixing: \( m_h < 116 \text{ GeV} \), no mixing in stop sector
- Gluophobic: \( m_h < 119 \text{ GeV} \), suppressed gg fusion
- Small \( \alpha \): \( m_h < 123 \text{ GeV} \), suppressed t\(\bar{t}\) h, h → bb
Enhanced coupling to 3rd generation:

- **Couplings:** $g_{\text{MSSM}} = \xi g_{\text{SM}}$

<table>
<thead>
<tr>
<th>$\xi$</th>
<th>t</th>
<th>b / $\tau$</th>
<th>W / Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>h</td>
<td>$\cos\alpha/\sin\beta$</td>
<td>-$\sin\alpha/\cos\beta$</td>
<td>$\sin(\alpha-\beta)$</td>
</tr>
<tr>
<td>H</td>
<td>$\sin\alpha/\sin\beta$</td>
<td>$\cos\alpha/\cos\beta$</td>
<td>$\cos(\alpha-\beta)$</td>
</tr>
<tr>
<td>A</td>
<td>$\cot\beta$</td>
<td>$\tan\beta$</td>
<td>-</td>
</tr>
</tbody>
</table>

$\alpha = \text{mixing angle between } h \text{ and } H$

Dominant production processes:

Branching ratios:

- $\text{BR}(A) \approx 10\%$
Final states considered:

1. “lepton-hadron”: \( \tau \tau \rightarrow \ell \tau_{\text{had}}(3\nu) \) with \( \ell = e/\mu \)
2. “lepton-lepton”: \( \tau \tau \rightarrow e\mu(4\nu) \)
3. “hadron-hadron”: \( \tau \tau \rightarrow \tau_{\text{had}}\tau_{\text{had}}(2\nu) \)

Signal and background samples:

<table>
<thead>
<tr>
<th>Signal process ((m_A = 120\text{GeV}, \tan\beta = 20))</th>
<th>(\sigma \times \text{BR} \ [\text{pb}])</th>
<th>Generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>( bbA/H/h(\rightarrow \tau \tau) ) ( m_h = 118\text{GeV} )</td>
<td>7.62/0.69/7.3</td>
<td>Sherpa</td>
</tr>
<tr>
<td>( gg \rightarrow A/H/h(\rightarrow \tau \tau) ) ( m_H = 130\text{GeV} )</td>
<td>4.93/2.21/4.1</td>
<td>POWHeg</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Background process</th>
<th>(\sigma \ [\text{pb}])</th>
<th>Generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W \rightarrow \ell \nu \ (\ell = e, \mu, \tau) )</td>
<td>(10.5 \times 10^3)</td>
<td>Alpgen</td>
</tr>
<tr>
<td>( Z/\gamma^* \rightarrow \ell^+\ell^- \ (m_{\ell\ell} &gt; 10\text{GeV}) )</td>
<td>(4.96 \times 10^3)</td>
<td>Alpgen/Pythia</td>
</tr>
<tr>
<td>( t\bar{t} )</td>
<td>165</td>
<td>MC@NLO</td>
</tr>
<tr>
<td>Single-top ((t-, s-) and (Wt)-channels)</td>
<td>58.7, 3.9, 13.1</td>
<td>MC@NLO/Acer</td>
</tr>
<tr>
<td>Di-boson ((WW, WZ) and (ZZ))</td>
<td>46.2, 18.0, 5.6</td>
<td>Herwig/MC@NLO</td>
</tr>
<tr>
<td>QCD multijet</td>
<td>???</td>
<td>–</td>
</tr>
</tbody>
</table>
Neutral MSSM Higgs Bosons – MMC

<table>
<thead>
<tr>
<th>Eff (%)</th>
<th>Z</th>
<th>120</th>
<th>150</th>
<th>200</th>
<th>250</th>
<th>300</th>
<th>400</th>
</tr>
</thead>
<tbody>
<tr>
<td>98</td>
<td>99</td>
<td>98</td>
<td>98</td>
<td>96</td>
<td>91</td>
<td>88</td>
<td></td>
</tr>
</tbody>
</table>
Neutral MSSM Higgs Bosons – $Z \rightarrow \tau \tau$ Background

- Reliable model of mass distribution shape is essential (low mass Higgs)
- Real $Z \rightarrow \tau \tau$ data would be ideal, but it cannot be selected signal free
- Instead: use high purity $Z \rightarrow \mu \mu$ sample ($\approx$ signal free, due to small Higgs muon coupling)
Select $Z \rightarrow \mu\mu$ data events

Remove muon tracks and nearby calorimeter cells

Simulate standalone $Z \rightarrow \tau\tau$ decays, so that $\tau$ four-momenta match the original muon ones

Merge into single MC-data hybrid event

Re-reconstruct objects and $E_T^{\text{miss}}$
Replaces $Z \rightarrow \tau\tau$ MC shapes in the following.
had-had:

**Z → ττ**

**W → τν**

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

Used as cross check.
Separate QCD estimates for all final states using an “ABCD”-method. 4 regions based on:

- **lepton-hadron:**
  Charge product and **lepton isolation**, \(\text{shape: region C}\)

- **lepton-lepton:**
  Charge product and **lepton isolation**, \(\text{shape: region B}\)

- **hadron-hadron:**
  Charge product and **Tau ID**, \(\text{shape: region B}\)

Subtract non QCD backgrounds in CRs B,C,D (for lep-had \(W^+\) jets normalization is fixed in high \(m_T\) region)

For lep-had, QCD in signal region A:

\[
 n_{A}^{QCD} = r_{B/D} \times n_{C}^{(\text{data} - \text{non QCD MC})}
\]

(similar for lep-lep & had-had)
Neutral MSSM Higgs Bosons – Estimation of QCD & W+jets in Lepton-Hadron

Basic idea and assumptions

Charge correlation: \( q_{lep} \times q_{\tau} = \)

\[ -1 \rightarrow "\text{Opposite Sign" (OS) Signal} \]

\[ +1 \rightarrow "\text{Same Sign" (SS)} \]

\[ \Rightarrow n_{Bkg}^{OS} = n_{SS}^{Bkg} + n_{QCD}^{OS-SR} + n_{W+Jets}^{OS-SR} + n_{Z}^{OS-SR} + n_{other}^{OS-SR} \approx 0 \]

- Data with \( q_{lep} \times q_{\tau} = +1 \)
- \( W+jets: n(OS) > n(SS) \)
  \[ \Rightarrow \text{W+jets Add-On} \]
  - Normalization from \( m_{T} > 50 \text{ GeV} \)
  - MMC mass shape from MC
- Shape and normalization for \( Z \rightarrow \tau \tau \) and other BGs from Embedding/MC

\[ \text{ATLAS Preliminary} \]

\[ \sqrt{s}=7\text{TeV}, \quad \int L=36\text{pb}^{-1} \]

\[ W+jets \text{ add-on} \]
- QCD multijet background from ABCD
- Other backgrounds taken from simulation
  - Corrections for trigger and tau “fake rate” applied
  - $W/Z$ MC cross-checked with embedding
- Tau trigger and ID efficiencies are measured in $Z \rightarrow \tau_{\text{had}} \tau_{\mu}$
- Fake tau trigger efficiency and tau fake rate measured in $W \rightarrow \mu\nu + \text{jets}$
Neutral MSSM Higgs Bosons – Cross-check of 2 Background Estimates – lep-had

Same-Sign method:

**ATLAS** Preliminary

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

\[ e^\tau_{\text{had}} + \mu^\tau_{\text{had}} \text{ channels} \]

Events / 10 GeV

 MMC \( m_{\tau\tau} \) [GeV]

\[ 0 \quad 50 \quad 100 \quad 150 \quad 200 \quad 250 \quad 300 \quad 350 \quad 400 \]

Data 2011

\[ A(120)/H/h \rightarrow \tau \tau, \tan\beta = 20 \]

\[ Z/\gamma^*(\rightarrow \tau\tau) \text{ emb. (OS-SS)} \]

Others (OS-SS)

W+jets (OS-SS)

Same Sign

stat.


ABCd method:

**ATLAS** Preliminary

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

\[ e^\tau_{\text{had}} + \mu^\tau_{\text{had}} \text{ channels} \]

Events / 10 GeV

 MMC \( m_{\tau\tau} \) [GeV]

\[ 0 \quad 50 \quad 100 \quad 150 \quad 200 \quad 250 \quad 300 \quad 350 \quad 400 \]

Data 2011

\[ A(120)/H/h \rightarrow \tau \tau, \tan\beta = 20 \]

\[ Z/\gamma^*(\rightarrow \tau\tau) \text{ emb.} \]

Others

W+jets

QCD multi-jet

stat.

Good agreement.
## Neutral MSSM Higgs Bosons – Systematics

### Table: Systematic Uncertainties

<table>
<thead>
<tr>
<th>II/lh/hh</th>
<th>W+jets</th>
<th>Di-boson</th>
<th>(t\bar{t})+ single-top</th>
<th>(Z/\gamma^* \to ee, \mu\mu)</th>
<th>(Z/\gamma^* \to \tau^+\tau^-)</th>
<th>Signal, (\tan\beta = 20)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>120/120/200GeV</td>
</tr>
<tr>
<td>(\sigma_{\text{inclusive}})</td>
<td>-/-/5</td>
<td>7</td>
<td>10</td>
<td>5/5/-</td>
<td>5</td>
<td>14/14/16</td>
</tr>
<tr>
<td>Acceptance</td>
<td>-/-/20</td>
<td>4/2/7</td>
<td>3/2/9</td>
<td>2/14/-</td>
<td>5/14/14</td>
<td>5/7/9</td>
</tr>
<tr>
<td>(e) efficiency</td>
<td>-/-/0.8</td>
<td>4/3.1/0.5</td>
<td>4/3.6/0.3</td>
<td>4/3.1/-</td>
<td>4/3.0/0.5</td>
<td>4/3.6/0.1</td>
</tr>
<tr>
<td>(\mu) efficiency</td>
<td>-/-/0.3</td>
<td>2/1.2/0.4</td>
<td>2/1.1/0.0</td>
<td>2/1.3/-</td>
<td>2/1.8/0.4</td>
<td>2/1.0/0.1</td>
</tr>
<tr>
<td>(\tau) efficiency/fake rate</td>
<td>-/-/21</td>
<td>-/-9.1/15</td>
<td>-/-9.1/13</td>
<td>-/-48/-</td>
<td>-/-9.1/15</td>
<td>-/-9.1/15</td>
</tr>
<tr>
<td>Energy scales/resolution</td>
<td>-/-/+34</td>
<td>2/+19/+26</td>
<td>6/+5</td>
<td>1/+39/-</td>
<td>1/11/+63</td>
<td>1/+30/+9</td>
</tr>
<tr>
<td>Luminosity</td>
<td>-/-/3.7</td>
<td>3.7</td>
<td>3.7</td>
<td>3.7/3.7/-</td>
<td>3.7</td>
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<tr>
<td>Total uncertainty</td>
<td>-/-/+45</td>
<td>10/+23/+32</td>
<td>13/15/23</td>
<td>8/+64/-</td>
<td>9/21/+67</td>
<td>16/+35/+26</td>
</tr>
</tbody>
</table>

### Background estimation:

- Same Sign stat. 17%
- OS/SS ratio 19%
- W normalization 11%
- Z embedding
Control samples, with only lepton ID changed:
- **Tight sample**, containing mostly true leptons
- **Loose sample**, containing mostly fake leptons (looser ID&Isolation)

Number of mis-IDed and real leptons: $N_{m}^{L}$, $N_{m}^{T}$, $N_{r}^{L}$, $N_{r}^{T}$

\[ N^{L} = N_{m}^{L} + N_{r}^{L} \]
\[ N^{T} = N_{m}^{T} + N_{r}^{T} \]

Number of mis-IDed events passing the selection is then defined as:

\[ N_{m}^{T} = \frac{p_{m}}{p_{r} - p_{m}} (p_{r} N^{L} - N^{T}) \]

with $p_{r} = \frac{N_{r}^{T}}{N_{r}^{L}}$ (from $Z \rightarrow \ell\ell$ events)

and $p_{m} = \frac{N_{m}^{T}}{N_{m}^{L}}$ (from multijet events)
<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Normalisation uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>lepton+jets:</strong></td>
<td></td>
</tr>
<tr>
<td>Generator and parton shower ((b\bar{b}WH^+)), signal region</td>
<td>10%</td>
</tr>
<tr>
<td>Generator and parton shower ((b\bar{b}W^+W^-)), signal region</td>
<td>8%</td>
</tr>
<tr>
<td>Generator and parton shower ((b\bar{b}WH^+)), control region</td>
<td>7%</td>
</tr>
<tr>
<td>Generator and parton shower ((b\bar{b}W^+W^-)), control region</td>
<td>6%</td>
</tr>
<tr>
<td>Initial and final state radiation (signal region)</td>
<td>8%</td>
</tr>
<tr>
<td>Initial and final state radiation (control region)</td>
<td>13%</td>
</tr>
<tr>
<td><strong>(\tau)+lepton:</strong></td>
<td></td>
</tr>
<tr>
<td>Generator and parton shower ((b\bar{b}WH^+))</td>
<td>2%</td>
</tr>
<tr>
<td>Generator and parton shower ((b\bar{b}W^+W^-))</td>
<td>5%</td>
</tr>
<tr>
<td>Initial and final state radiation</td>
<td>13%</td>
</tr>
<tr>
<td><strong>(\tau)+jets:</strong></td>
<td></td>
</tr>
<tr>
<td>Generator and parton shower ((b\bar{b}WH^+))</td>
<td>5%</td>
</tr>
<tr>
<td>Generator and parton shower ((b\bar{b}W^+W^-))</td>
<td>5%</td>
</tr>
<tr>
<td>Initial and final state radiation</td>
<td>19%</td>
</tr>
<tr>
<td>Source of uncertainty</td>
<td>Normalisation uncertainty</td>
</tr>
<tr>
<td>---------------------------------------------------------</td>
<td>---------------------------</td>
</tr>
<tr>
<td>lepton+jets: lepton misidentification</td>
<td></td>
</tr>
<tr>
<td>Choice of control region</td>
<td>6%</td>
</tr>
<tr>
<td>Z mass window</td>
<td>4%</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>16%</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>7%</td>
</tr>
<tr>
<td>Sample composition</td>
<td>31%</td>
</tr>
<tr>
<td>ρ+lepton: jet→τ misidentification</td>
<td>2%</td>
</tr>
<tr>
<td>Statistics in control region</td>
<td>11%</td>
</tr>
<tr>
<td>Object-related systematics</td>
<td>23%</td>
</tr>
<tr>
<td>τ+lepton: e→τ misidentification</td>
<td>4%</td>
</tr>
<tr>
<td>Misidentification probability</td>
<td>20%</td>
</tr>
<tr>
<td>τ+lepton: lepton misidentification</td>
<td></td>
</tr>
<tr>
<td>Choice of control region</td>
<td>4%</td>
</tr>
<tr>
<td>Z mass window</td>
<td>5%</td>
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<tr>
<td>Jet energy scale</td>
<td>14%</td>
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<tr>
<td>Jet energy resolution</td>
<td>4%</td>
</tr>
<tr>
<td>Sample composition</td>
<td>39%</td>
</tr>
<tr>
<td>τ+jets: true τ</td>
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<tr>
<td>Embedding parameters</td>
<td>6%</td>
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<tr>
<td>Muon isolation</td>
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<tr>
<td>Parameters in normalisation</td>
<td>16%</td>
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<tr>
<td>τ identification</td>
<td>5%</td>
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<tr>
<td>τ energy scale</td>
<td>6%</td>
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<tr>
<td>τ+jets: jet→τ misidentification</td>
<td>2%</td>
</tr>
<tr>
<td>Jet composition</td>
<td>12%</td>
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<tr>
<td>Purity in control region</td>
<td>6%</td>
</tr>
<tr>
<td>Object-related systematics</td>
<td>21%</td>
</tr>
<tr>
<td>τ+jets: e→τ misidentification</td>
<td>4%</td>
</tr>
<tr>
<td>Misidentification probability</td>
<td>22%</td>
</tr>
<tr>
<td>τ+jets: multi-jet estimate</td>
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</tr>
<tr>
<td>Fit-related uncertainties</td>
<td>32%</td>
</tr>
<tr>
<td>E_{T}^{miss}.shape in control region</td>
<td>16%</td>
</tr>
</tbody>
</table>
### Doubly Charged Higgs – Yields and More Plots

#### Sample

<table>
<thead>
<tr>
<th>Sample</th>
<th>Number of muon pairs with $m(\mu^+\mu^+)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$&gt; 15$ GeV</td>
</tr>
<tr>
<td>prompt muons</td>
<td>63.1 ± 7.8</td>
</tr>
<tr>
<td>non-prompt muons</td>
<td>37.5 ± 10.3</td>
</tr>
<tr>
<td>charge flip</td>
<td>0.2 ± 0.7</td>
</tr>
<tr>
<td>total</td>
<td>100.6 ± 13.2</td>
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<tr>
<td>data</td>
<td>101</td>
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</table>

#### Sample

<table>
<thead>
<tr>
<th>Sample</th>
<th>Number of muon pairs with $m(\mu^+\mu^-)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$&gt; 15$ GeV</td>
</tr>
<tr>
<td>prompt muons</td>
<td>41.2 ± 5.3</td>
</tr>
<tr>
<td>non-prompt muons</td>
<td>20.2 ± 6.9</td>
</tr>
<tr>
<td>charge flip</td>
<td>0.3 ± 0.7</td>
</tr>
<tr>
<td>total</td>
<td>61.4 ± 9.0</td>
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<tr>
<td>data</td>
<td>61</td>
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</table>

#### Sample

<table>
<thead>
<tr>
<th>Sample</th>
<th>Number of muon pairs with $m(\mu^-\mu^-)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$&gt; 15$ GeV</td>
</tr>
<tr>
<td>prompt muons</td>
<td>21.9 ± 3.0</td>
</tr>
<tr>
<td>non-prompt muons</td>
<td>17.4 ± 4.7</td>
</tr>
<tr>
<td>charge flip</td>
<td>0.3 ± 0.7</td>
</tr>
<tr>
<td>total</td>
<td>39.3 ± 6.5</td>
</tr>
<tr>
<td>data</td>
<td>40</td>
</tr>
</tbody>
</table>
### NMSSM $a_1 \rightarrow \mu \mu$ Systematic Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Relative Uncertainty (%) at $m(a_1)$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6.0</td>
</tr>
<tr>
<td>Luminosity</td>
<td>±3</td>
</tr>
<tr>
<td><strong>PYTHIA vs MC@NLO</strong></td>
<td>±67</td>
</tr>
<tr>
<td>Dimuon Efficiency</td>
<td>+14</td>
</tr>
<tr>
<td>Trigger Correction</td>
<td>−13</td>
</tr>
<tr>
<td>MC Statistics</td>
<td>±10</td>
</tr>
<tr>
<td>Likelihood Ratio Modeling</td>
<td>±3</td>
</tr>
<tr>
<td>Total (Pythia vs MC@NLO)</td>
<td>±70</td>
</tr>
</tbody>
</table>