Search for BSM Higgs Bosons
with ATLAS

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On behalf of the ATLAS Collaboration

SEARCH 2012 Workshop
University of Maryland, March 17-19, 2012
Overview

- Fermiophobic $H \to \gamma\gamma$

- MSSM neutral $h/H/A \to \tau\tau$

- Charged Higgs bosons
  - $H^+ \to \tau_{\text{had}}\nu$
  - $H^+ \to \tau_{\text{lep}}\nu$
  - $H^+ \to c\bar{s}$

- Doubly charged Higgs $H^{++} \to \mu^+\mu^+$

- NMSSM $a_1 \to \mu\mu$

New prelim. results (4.6 fb$^{-1}$)

New prelim. results (4.9 fb$^{-1}$)

Published in PRD (1.6 fb$^{-1}$)
Fermiophobic Higgs

• **Suppressed Higgs couplings to fermions** in 2HDM and Higgs triplet models
  
  Here: simple benchmark model (LEP)
  - no fermion-Higgs couplings
  - SM boson-Higgs couplings

• **Production**: Vector-boson fusion and associated production with W/Z

• **Decays** to $\gamma\gamma$, WW, ZZ, $Z\gamma$
  
  Here: focus on $H \rightarrow \gamma\gamma$
  
  $\Rightarrow$ **larger $\sigma \times BR$** than SM for light Higgs
  $\Rightarrow$ **higher Higgs $p_T$**
Fermiophobic Higgs → γγ

- **Selection**: (identical to SM H → γγ)
  - 2 isolated photons with $p_T > 40, 20$ GeV
  - Di-photon mass: $100 < m_{\gamma\gamma} < 160$ GeV
- **9 categories** based on
  - presence of γ conversions
  - γ calorimeter impact point
  - $p_{Tt}$: related to di-photon $p_T$

- **Signal $m_{\gamma\gamma}$ model**
  Crystal Ball (core) + wide Gaussian (tail)

- **Background $m_{\gamma\gamma}$ model**
  Exponential
**Fermiophobic Higgs → γγ: Exclusion limits**

**Observed** $m_H$ exclusion:
[110.0, 118.0], [119.5, 121.0]

**Expected** $m_H$ exclusion:
[110.0, 123.5]

Largest excess at $m_H$=125.5 GeV

Including look-elsewhere effect:
Significance: 1.6σ
Prob. of background fluctuation: 5%
Neutral MSSM Higgs

- **MSSM** requires 2 Higgs doublets ⇒ 5 Higgs bosons: \( \Phi = h, H, A; H^+, H^- \)
  - \( h/H \) and \( A \) nearly mass degenerate
  - 2 parameters at tree level: \( m_A, \tan\beta \)
  - Enhanced couplings to \( b \) and \( \tau \) in large parts of parameter space
    \( \sigma_{bbh/H/A} \propto \tan^2\beta \)
Tau signature and identification

Hadronic $\tau$ decay ($\tau_{\text{had}}$):

- Narrow, collimated jet
- Isolated energy deposits and tracks
- Large electromagnetic component
- Low track multiplicity (1 or 3)
- High leading track momentum fraction

**Multivariate identification**
Neutral MSSM Higgs : Selection

**e + μ**
- 1 isolated e with $p_T > 25$ GeV
- 1 isolated μ with $p_T > 20$ GeV
- Opposite charges
- $E_T^{\text{miss}} + p_T^e + p_T^\mu < 120$ GeV
- $\Delta \Phi(e,\mu) > 2.0$ rad
  (top, WW, ZZ suppression)

**e/μ + τ_{had}**
- 1 isolated e / μ with $p_T > 25 / 20$ GeV
- 1 $\tau_{had}$ with $p_T > 20$ GeV
- Opposite charges
- Di-lepton veto (Z, top)
- $E_T^{\text{miss}} > 20$ GeV (QCD)
- $m_T < 30$ GeV (W)

**τ_{had} + τ_{had}**
- Di-τ_{had} trigger
- 2 $\tau_{had}$ with $p_T > 45 / 30$ GeV
- Opposite charges
- $E_T^{\text{miss}} > 25$ GeV
  (QCD suppression)
Neutral MSSM Higgs: Mass reconstruction

- **Visible mass**: $m_{\tau\tau}^{\text{visible}}$ (invariant mass of visible tau decay products)

- **Effective mass**:
  
  $$m_{\tau\tau}^{\text{effective}} = \sqrt{(p_{\tau^+} + p_{\tau^-} + p_{\text{miss}})^2}$$

  $$p_{\text{miss}} = (E_T^{\text{miss}}, E_x^{\text{miss}}, E_y^{\text{miss}}, 0)$$

- **Missing mass calculator (MMC)**:

  - 7 unknown parameters:
    - two “missing” 3-momenta, $m_{\nu\nu}$
  
  - 4 constraints from $E_x^{\text{miss}}, E_y^{\text{miss}}, m_{\tau1}, m_{\tau2}$

  $\Rightarrow$ scan over $\Delta\Phi(\nu,l), \Delta\Phi(\nu,h), m_{\nu\nu}$

  $\Rightarrow$ weight solution according to probability of 3D angle in solution

  $\Rightarrow$ MMC mass = Max. of weighted $m_{\tau\tau}$ distribution

Neutral MSSM Higgs: Background estimation

Background estimation based on data control samples:

- **$Z/\gamma^* \rightarrow \tau\tau$ from $\tau$-embedded**
  - $Z/\gamma^* \rightarrow \mu\mu$ data sample

- **Multijet** background from samples with same-sign charges and low $E_T^{\text{miss}}$ or inverted lepton isolation

- **W+jets** from high-$m_T(l,E_T^{\text{miss}})$ sample

- No significant charge correlation
- Expect no large $E_T^{\text{miss}}$
- Mostly non-isolated or fake leptons
Neutral MSSM Higgs: Results

**e + µ**

<table>
<thead>
<tr>
<th>Final state</th>
<th>Exp. Background</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>eµ</td>
<td>$(2.6 \pm 0.2) \times 10^3$</td>
<td>2472</td>
</tr>
<tr>
<td>ℓτ(_{\text{had}})</td>
<td>$(2.1 \pm 0.4) \times 10^3$</td>
<td>1913</td>
</tr>
<tr>
<td>τ(<em>{\text{had}})τ(</em>{\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: Exclusion limits

- Assume only one resonance ($\Phi$):
  - 100% $gg \rightarrow \Phi$ or
  - 100% $bb\Phi$ production
    (acceptances similar)

- Useful to test arbitrary models

- Need to assume specific (c)MSSM scenario

Here: $m_h^{\text{max}}$ scenario

$\sigma \times \text{BR} (\Phi \rightarrow \tau\tau)$

$(m_A, \tan\beta)$ plane

$\sqrt{s} = 7 \, \text{TeV}, \int L dt = 1.06 \, \text{fb}^{-1}$
Neutral MSSM Higgs: Exclusion limits

Comparison of search channels

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

ATLAS Preliminary

Update to full 4.9 fb$^{-1}$ data set & inclusion of b-tagging in progress!
Charged Higgs

- Predicted in Higgs doublet (e.g. MSSM) and triplet models
- $m_{H^+} < m_t$: dominant production in top quark decays
- $m_{H^+} > m_t$: $gb \rightarrow tH^+$ production important, but more data needed
- for $\tan\beta > 3$, preferred decay mode is $H \rightarrow \tau\nu$ (here: assume BR of 100%%)

$$\begin{align*}
\bar{t}t &\rightarrow b\bar{b}H^\pm W^\mp \rightarrow b\bar{b}(\tau_{lep}\nu)(q\bar{q}) : \text{lepton + jets} \\
t\bar{t} &\rightarrow b\bar{b}H^\pm W^\mp \rightarrow b\bar{b}(\tau_{had}\nu)(\ell\nu) : \tau_{had} + \text{lepton} \\
t\bar{t} &\rightarrow b\bar{b}H^\pm W^\mp \rightarrow b\bar{b}(\tau_{had}\nu)(q\bar{q}) : \tau_{had} + \text{jets}
\end{align*}$$
Charged Higgs: Lepton + jets channel

Selection:

- 1 isolated $e / \mu$ with $p_T > 25 / 20 \text{ GeV}$
- $\geq 4$ jets (2 b-tagged) with $p_T > 20 \text{ GeV}$
- $E_{T}^{\text{miss}} > 40 \text{ GeV}$ if $|\Phi_{l,\text{miss}}| > \pi/6$
- $E_{T}^{\text{miss}} \times |\sin(\Phi_{l,\text{miss}})| > 20 \text{ GeV}$ if $|\Phi_{l,\text{miss}}| < \pi/6$
- Identify "hadronic side" by choosing combination of 1 b-jet and 2 light jets that minimizes

$$
\chi^2 = \frac{(m_{jjb} - m_{top})^2}{\sigma_{top}^2} + \frac{(m_{jj} - m_W)^2}{\sigma_W^2}
$$

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

Discriminating variables:

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

- Lower bound ~ mass of charged boson ($H^+$ or $W$)
- Discriminates between leptons from $\tau$ and W
Charged Higgs: Lepton + jets channel

Signal region: \( \cos \theta^*_{l} < -0.6 \), \( m_T(l, E_{T}^{miss}) < 60 \text{ GeV} \)

Dominant background from top pairs!
Simulated with MC@NLO, normalized in \(-0.2 < \cos \theta^*_{l} < 1\)

Misidentified-lepton background determined from control sample with loosened lepton ID
Charged Higgs: $\tau_{\text{had}} + \text{lepton channel}$

Selection:
- 1 isolated $e / \mu$ with $p_T > 25 / 20$ GeV
- 1 $\tau_{\text{had}}$ with $p_T > 20$ GeV
- $\geq 2$ jets (≥ 1 b-tagged) with $p_T > 20$ GeV
- Sum of primary-vertex track $p_T$: $\Sigma p_T > 100$ GeV

Discriminating variable: $E_T^{\text{miss}}$

- Background contributions with misidentified taus:
  $\mu$: 0.05%, $e$: 1%, jets: 55%; jet → $\tau_{\text{had}}$ mis-ID measured with $W+jets$

- True-tau background taken from simulation
A candidate event in $\tau_{\text{had}} + \text{lepton channel}$
Charged Higgs: $\tau_{\text{had}} + \text{jets}$ channel

**Selection:**
- $\tau + E_T^{\text{miss}}$ trigger
- 1 $\tau_{\text{had}}$ with $p_T > 40$ GeV
- $\geq 4$ jets ($\geq 1$ b-tagged) with $p_T > 20$ GeV
- $E_T^{\text{miss}} > 65$ GeV
- $E_T^{\text{miss}}$ significance: $\frac{E_T^{\text{miss}}}{0.5 \cdot \sqrt{\sum p_T}} > 13$ GeV$^{1/2}$
- jjb combination (highest $p_T$) consistent $m_{\text{top}}$

**Discriminating variable:**

$$m_T = \sqrt{2p_T^\tau E_T^{\text{miss}} (1 - \cos \phi_{\tau, \text{miss}})}.$$

- **True-tau background** estimated with $\tau$ embedding in $\mu$+jets events (with top-pair like event topology)
- **Mis-id. tau background:** as for $\tau_{\text{had}}$+lepton
Charged Higgs: $\tau_{\text{had}} + \text{jets}$ channel

<table>
<thead>
<tr>
<th>Sample</th>
<th>Event yield ($\tau$+jets)</th>
</tr>
</thead>
<tbody>
<tr>
<td>True $\tau$ (embedding method)</td>
<td>$210 \pm 10 \pm 44$</td>
</tr>
<tr>
<td>Misidentified jet $\rightarrow$ $\tau$</td>
<td>$36 \pm 6 \pm 10$</td>
</tr>
<tr>
<td>Misidentified $e \rightarrow$ $\tau$</td>
<td>$3 \pm 1 \pm 1$</td>
</tr>
<tr>
<td>Multi-jet processes</td>
<td>$74 \pm 3 \pm 47$</td>
</tr>
<tr>
<td>$\sum$ SM</td>
<td>$330 \pm 12 \pm 65$</td>
</tr>
<tr>
<td>Data</td>
<td>$355$</td>
</tr>
<tr>
<td>$t \rightarrow bH^+$ (130 GeV)</td>
<td>$220 \pm 6 \pm 56$</td>
</tr>
</tbody>
</table>

Multijet background estimated by fitting $E_T^{\text{miss}}$ shapes to data.

Multijet shape from control sample with inverted $\tau$ and b ID.
Charged Higgs: Exclusion limits

Tevatron limits:
BR < 10-15%

ATLAS-CONF-2012-011
Charged Higgs: Exclusion limits (MSSM)

...we will probably be able to rule out low-mass charged Higgs with 2012 data, if it doesn’t exist!
Charged Higgs: $H^+ \rightarrow c\bar{s}$

- $H \rightarrow c\bar{s}$ dominates for $\tan\beta < 1$

- Require **large** $E_T^{\text{miss}}$ and $m_T$ to suppress multijet background

- **Kinematic fit** with $W$ and top mass constraints to find best $H^+$ candidate

- Set limits on BR($t \rightarrow H^+b$) assuming $\text{BR}(H^+ \rightarrow c\bar{s}) = 100\%$
Doubly-charged Higgs

- Relevant e.g. in Higgs triplet, Little Higgs and Left-Right Symmetric models

- Select $\mu$ pairs with same-sign charges and $p_T > 20$ GeV

- Look for resonance in $\mu^\pm \mu^\pm$ mass spectrum

- No significant excess over SM background found
Doubly-charged Higgs: Exclusion limits

Set limits on $H^{++} H^{-}$ pair production via Drell Yan process $pp \rightarrow Z/\gamma^* \rightarrow H^{++} H^{-}$

Assuming predicted cross section, set limits on BR

Tevatron (CDF) upper limit: 205-245 GeV

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

**NMSSM** a₁ → μ⁺μ⁻

- **NMSSM**: introduces singlet scalar field to solve μ problem
  ⇒ 3 CP-even scalars (h₁, h₂, h₃)
  2 CP-odd scalars (a₁, a₂)
- a₁ can be very light!
  \( m_{a₁} < 2 m_B \)

**Analysis:**
- Opposite-sign di-muons \( (P_T > 4 \text{GeV}) \)
- Likelihood ratio selection based on \( \mu^+\mu^- \) vertex \( \chi^2 \) and \( \mu \) isolation
- Set limits by fitting to mass spectrum
- Y region excluded
Conclusions

• Various interesting BSM Higgs scenarios are being probed in parallel to SM Higgs search

• No indication for BSM Higgs bosons yet … but lots of upper limits on cross sections/branching ratios

• Searches continue with more data and improved methods ⇒ There is still significant room for BSM Higgs searches for the year ahead … and after!
Fermiophobic Higgs $\rightarrow \gamma\gamma$: Exclusion limits
Fermiophobic Higgs $\rightarrow \gamma\gamma$ : Systematics

<table>
<thead>
<tr>
<th>Event Source</th>
<th>Systematic Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon reconstruction and identification</td>
<td>$\pm 11%$</td>
</tr>
<tr>
<td>Effect of pileup on photon identification</td>
<td>$\pm 4%$</td>
</tr>
<tr>
<td>Isolation cut efficiency</td>
<td>$\pm 5%$</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>$\pm 1%$</td>
</tr>
<tr>
<td>Higgs boson cross section</td>
<td>$\pm 9%$</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$\pm 3.9%$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mass Source</th>
<th>Systematic Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calorimeter energy resolution</td>
<td>$\pm 12%$</td>
</tr>
<tr>
<td>Photon energy calibration</td>
<td>$\pm 6%$</td>
</tr>
<tr>
<td>Effect of pileup on energy resolution</td>
<td>$\pm 3%$</td>
</tr>
<tr>
<td>Photon angular resolution</td>
<td>$\pm 1%$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Category Migration</th>
<th>Systematic Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higgs boson $p_T$ modelling</td>
<td>$\pm 1%$</td>
</tr>
<tr>
<td>Conversion rate</td>
<td>$\pm 4.5%$</td>
</tr>
</tbody>
</table>

| Background Model                                    | $\pm (0.1 - 7.9)$ events |
MSSM Higgs sector

- MSSM: 2 Higgs doublets $\Rightarrow$ 5 Higgs bosons:
  $h^0$ (CP=1), $H^0$ (CP=1), $A^0$ (CP=-1), $H^\pm$

- At tree level described by two parameters: $m_A$, $\tan\beta = v_u/v_d$

- 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 (depend on SUSY parameters, e.g. mixing in stop sector)

All parameters except $\tan\beta$, $m_A$ fixed in benchmark scenarios:

- $m_h^{\text{max}}$: $m_h < 133$ GeV, maximum allowed mass for $h$
- nomixing: $m_h < 116$ GeV, no mixing in stop sector
- gluophobic: $m_h < 119$ GeV, suppressed gg fusion
- small $\alpha$: $m_h < 123$ GeV, suppressed $t\bar{t}h$, $h \rightarrow bb$
MSSM Higgs production

\[ gg \rightarrow b\bar{b}H \]

\[ bg \rightarrow bH \]

\[ b\bar{b} \rightarrow H \]
Estimation of $Z \rightarrow \tau \tau$ Background

- Reliable $Z \rightarrow \tau \tau$ model important for low-mass Higgs
- Desirable to use real data, but cannot be selected signal-free
- Instead, use high-purity $Z \rightarrow \mu \mu$ sample (~ signal-free due to small Higgs-μ coupling)
Z $\rightarrow \tau \tau$ “Embedding”: Method

- In $Z \rightarrow \mu \mu$ events, remove muon tracks and nearby calorimeter cells

- Simulate stand-alone $Z \rightarrow \tau \tau$ decays with same 4-momenta for the $\tau$'s as for the muons (after mass correction)

- Merge into single hybrid event and re-reconstruct objects and $E_T^{\text{miss}}$
Neutral MSSM Higgs: Background Estimation

• Estimate background from same-sign (SS) data sample

\[ n_{OS}^{Bkg} = n_{SS}^{Bkg} + n_{OS-SS}^{QCD} + n_{OS-SS}^{W} + n_{OS-SS}^{Z} + n_{OS-SS}^{other} \]

\[ \approx n_{SS}^{Bkg} + n_{OS-SS}^{W} + n_{OS-SS}^{Z} + n_{OS-SS}^{other} \]

• Assumption made for QCD:

\[ r_{QCD} = n(OS)/n(SS) \approx 1 \]

Checked with QCD-enhanced sample
- \( E_T^{miss} < 15 \) GeV
- loosened lepton isolation

\[ r_{QCD} = 1.16 \pm 0.04^{stat} \pm 0.09^{syst} \]

\[ r_{QCD}^{MC} = 1.06 \pm 0.13^{stat} \]
Neutral MSSM Higgs: Background Estimation

\[ n_{Bkg}^{OS} \approx n_{SS}^{Bkg} + n_{W}^{OS-SS} + n_{Z}^{OS-SS} + n_{other}^{OS-SS} \]

OS-SS “add-on” due to \( r_{OS/SS} \neq 1 \)

- \( n_{SS} \) from nominal selection with \( Q(\ell) \cdot Q(\tau) = +1 \)
- \( Z \rightarrow \tau^+\tau^- \) and other background OS-SS “add-on” from simulation
- \( W+\text{jets} \) OS-SS “add-on”:
  from \( M_T > 50 \text{ GeV} \) control sample
Neutral MSSM Higgs: Systematics

Table 4: Uncertainties on the number of selected events for those background contributions that are at least partially estimated from simulation and for a hypothetical signal ($m_A = 120$ GeV and $\tan \beta = 20$ for the $e\mu$ and $\ell\tau_{\text{had}}$ final states and $m_A = 200$ GeV and $\tan \beta = 20$ for the $\tau_{\text{had}}\tau_{\text{had}}$ final state). All numbers are given in %. When three numbers are given the first refers to the $e\mu$ final state, the second to the $\ell\tau_{\text{had}}$ final states and the third to the $\tau_{\text{had}}\tau_{\text{had}}$ final state. If an uncertainty does not apply for a certain background, this is indicated by a “-.” For the $e\mu$ final state, the uncertainty on the $W+$jets background is dominated by the statistical component and the systematic uncertainty is neglected; for the $\ell\tau_{\text{had}}$ final state the $W+$jets background is estimated from data.

<table>
<thead>
<tr>
<th></th>
<th>$W+$jets</th>
<th>Di-boson</th>
<th>$t\bar{t}$+</th>
<th>$Z/\gamma^* \to ee,\mu\mu$</th>
<th>$Z/\gamma^* \to \tau^+\tau^-$</th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<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 and 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 and resolution</td>
<td>-/-34/-21</td>
<td>2/-9 +/-26</td>
<td>6/+5/-12</td>
<td>1/-39/-</td>
<td>1/11/-/-63</td>
<td>1/-23/-8</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>
<td>3.7</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>-/-45/-36</td>
<td>10/-23/-32</td>
<td>13/15/23</td>
<td>8/-64/-/-36</td>
<td>9/21/-/-67</td>
<td>16/-35/-26</td>
</tr>
</tbody>
</table>
**H⁺: Estimation of mis-ID lepton background**

**Misidentified-lepton** background determined from samples with **tight** (T) and **loose** (L) lepton ID:

\[
\begin{align*}
N^L &= N^L_m + N^L_r \\
N^T &= N^T_m + N^T_r \\
N^T_m &= \frac{p_m}{p_r - p_m} (p_r N^L - N^T) \\
\end{align*}
\]

with \( p_r = \frac{N^T_r}{N^L_r} \) and \( p_m = \frac{N^T_m}{N^L_m} \)

from \( Z \rightarrow e^+e^- \) \hspace{1cm} \text{from multi-jets}

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## Charged Higgs: Systematics

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Normalisation uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>lepton+jets:</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>$\tau$+lepton:</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>$\tau$+jets:</td>
<td></td>
</tr>
<tr>
<td>Generator and parton shower ($b\bar{b}WH^+$)</td>
<td>5%</td>
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</tr>
<tr>
<td>Initial and final state radiation</td>
<td>19%</td>
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</tbody>
</table>
## Charged Higgs: Systematics

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Normalisation uncertainty</th>
<th>Shape uncertainty</th>
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<tbody>
<tr>
<td>lepton+jets: lepton misidentification</td>
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<tr>
<td>Choice of control region</td>
<td>6%</td>
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</tr>
<tr>
<td>Z mass window</td>
<td>4%</td>
<td>-</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>16%</td>
<td>-</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>7%</td>
<td>-</td>
</tr>
<tr>
<td>Sample composition</td>
<td>31%</td>
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<tr>
<td>$\tau$+lepton: jet$\to\tau$ misidentification</td>
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<td>Statistics in control region</td>
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<tr>
<td>Jet composition</td>
<td>11%</td>
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<tr>
<td>Object-related systematics</td>
<td>23%</td>
<td>3%</td>
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<tr>
<td>$\tau$+lepton: e$\to\tau$ misidentification</td>
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<td></td>
</tr>
<tr>
<td>Misidentification probability</td>
<td>20%</td>
<td>-</td>
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<tr>
<td>$\tau$+lepton: lepton misidentification</td>
<td></td>
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</tr>
<tr>
<td>Choice of control region</td>
<td>4%</td>
<td>-</td>
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<tr>
<td>Z mass window</td>
<td>5%</td>
<td>-</td>
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<tr>
<td>Jet energy scale</td>
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<tr>
<td>Jet energy resolution</td>
<td>4%</td>
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<tr>
<td>Sample composition</td>
<td>39%</td>
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<tr>
<td>$\tau$+jets: true $\tau$</td>
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<tr>
<td>Embedding parameters</td>
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<td>3%</td>
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<tr>
<td>Muon isolation</td>
<td>7%</td>
<td>2%</td>
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<tr>
<td>Parameters in normalisation</td>
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<tr>
<td>$\tau$ identification</td>
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<td>-</td>
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<tr>
<td>$\tau$ energy scale</td>
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<td>1%</td>
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<tr>
<td>$\tau$+jets: jet$\to\tau$ misidentification</td>
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<tr>
<td>Statistics in control region</td>
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<td>Jet composition</td>
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<td>Purity in control region</td>
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<td>1%</td>
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<tr>
<td>Object-related systematics</td>
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<td>2%</td>
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<tr>
<td>$\tau$+jets: e$\to\tau$ misidentification</td>
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<tr>
<td>Misidentification probability</td>
<td>22%</td>
<td>-</td>
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<tr>
<td>$\tau$+jets: multi-jet estimate</td>
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<td>Fit-related uncertainties</td>
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<tr>
<td>$E_T^{miss}$-shape in control region</td>
<td>16%</td>
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</table>
### Doubly-Charged Higgs: Event yields

<table>
<thead>
<tr>
<th>Sample</th>
<th>Number of muon pairs with $m(\mu^+\mu^-)$</th>
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<tbody>
<tr>
<td></td>
<td>$&gt; 15$ GeV</td>
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<tr>
<td>prompt muons</td>
<td>63.1 ± 7.8</td>
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<tr>
<td>non-prompt muons</td>
<td>37.5^{+10.3}_{-12.4}</td>
</tr>
<tr>
<td>charge flip</td>
<td>0^{+2.7}_{-0.0} ± 0.9</td>
</tr>
<tr>
<td>total</td>
<td>100.6^{+13.2}_{-14.7}</td>
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<tr>
<td>data</td>
<td>101</td>
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</table>

### Muon pairs / 25 GeV

#### Positively charged pairs

#### Negatively charged pairs

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NMSSM $a_1 \rightarrow \mu^+\mu^-$: Additional Plots
**NMSSM $a_1 \rightarrow \mu^+\mu^-$: Systematics**

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