Studies of the NMSSM Higgs decaying to four taus with the ATLAS detector using a new hadronic tau reconstruction algorithm

Master’s Thesis Defense
ICEPP Meeting Room
14th Jan 2011

Khaw Kim Siang
Outline

• Experimental setup
  LHC and ATLAS experiment, Data Taking
• Introduction
  NMSSM model and Benchmark points
• Event Topology
  From Higgs to four tau leptons
• Hadronic Tau
  ATLAS Default and NMSSM Exclusive Hadronic Tau Reconstruction
• Physics Analysis
  VBF Exclusive Analysis @ 7 TeV and 14 TeV, Inclusive Analysis @ 7 TeV
• Summary and discussion
LHC and ATLAS experiment

EXPERIMENTAL SETUP
Large Hadron Collider (LHC)
Circumference ~ 27 km
Superconductor Magnet = 8.33T @ T=1.9K
$10^{11}$ protons per bunch, 40MHz
World Highest Energy (14 TeV)
Designed Luminosity of $L=10^{34}$ cm$^{-2}$ s$^{-1}$

A Toroidal LHC ApparatuS (ATLAS)
Multipurpose Detector
Superconducting Solenoid = 2T
Width 44m, Height 22m, 7000t
Aiming at the discovery of Higgs, SUSY, Extra Dimension, BlackHole, +....???

Reached Luminosity $\sim 2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$ @ 7 TeV on 8th Nov 2010 !!!
Data taking

Great job done by **LHC** team
Total delivered integrated luminosity of **48.1 pb⁻¹**.

Fantastic performance of **ATLAS** detector **45.0 pb⁻¹** of data recorded, with > 90% of good quality data delivered.

<table>
<thead>
<tr>
<th>Inner Tracking Detectors</th>
<th>Calorimeters</th>
<th>Muon Detectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel  SCT  TRT</td>
<td>LAr EM LAr HAD LAr FWD Tile MDT RPC CSC TGC</td>
<td></td>
</tr>
<tr>
<td>99.0  99.9  100</td>
<td>90.5 96.6 97.8 94.3 99.9 99.8 96.2 99.8</td>
<td></td>
</tr>
</tbody>
</table>

Luminosity weighted relative detector uptime and good quality data delivery during 2010 stable beams in pp collisions at $\sqrt{s}=7$ TeV between March 30th and October 31st (in %). The inefficiencies in the calorimeters will largely be recovered in a future data reprocessing.

For **this thesis**, **34.8 pb⁻¹** of data is analyzed. (Required all relevant detectors to be functioning.)
Physics Motivation of NMSSM model

INTRODUCTION
Theoretically

- SUSY is one of the solutions to SM Higgs mass divergence problem.
- However, minimal SUSY model (MSSM) has μ problem. It does not explain why μ is at electroweak scale. \( W_{\text{MSSM}} = \ldots + \mu H_u H_d \)
- By adding a singlet superfield \( S \), we can dynamically generate the μ term in MSSM. \( \text{NMSSM} \rightarrow W_{\text{NMSSM}} = \ldots + \lambda S H_u H_d, \mu_{\text{eff}} = \lambda <S> \)
- NMSSM solved μ problem in MSSM.

Experimentally

- To be consistent with experimental data (LEP), we must have, SM Higgs > 114.4 GeV or non-SM Higgs decay mode if they exist.
- NMSSM with non-SM Higgs decay mode is a good candidate.
  (Higgs to higgs decays)
Next to the Minimal Supersymmetry Standard Model

6 free parameters: $\mu, \lambda, \kappa, A_\lambda, A_\kappa, \tan\beta$

Too complicated and hard to interpret.

→ Study proposed benchmarked points!

(4 parameters fixed → 2 free parameters)

Reduced coupling scenario, **Light $A_1$ scenario** and maximal $H_1$ scenario

\[
A_\lambda = -580 \text{ GeV}, \quad A_\kappa = -2.8 \text{ GeV}, \quad \mu = -520 \text{ GeV}, \quad \tan\beta = 5.0
\]

\[
M_1 = 500 \text{ GeV}, \quad M_2 = 1 \text{ TeV}, \quad M_3 = 3 \text{ TeV}, \quad M_{\text{Susy}} = 1 \text{ TeV}, \quad A_t = A_b = A_\tau = 1.5 \text{ TeV}
\]

7 Higgs

CP-even: $H_1, H_2, H_3, H^\pm$

CP-odd: $A_1, A_2$

H$_1$ mass of around 120 GeV
A_1 mass of around 5 GeV, BR(H1→A1A1)~100%
BR(A→ττ)~90%, VBF coupling ~SM
From Higgs to Four Tau Leptons

EVENT TOPOLOGY
Non-SM Higgs Decay Mode

For NMSSM

Light A1 scenario = 100%
Typically = 90%

\[ m_{A_1} < 2m_b \]

\( h (H_1) \) : lightest CP-even higgs in NMSSM (SM-like)
\( a (A_1) \) : lightest CP-odd higgs in NMSSM

\[ m_h = 100 - 120 \text{ GeV} \]
\[ m_a = 4 - 8 \text{ GeV} \]
in our analysis

Higgs production process - vector boson fusion (VBF)

- Two high pt **forward jets**.
- Only Higgs decay products detected at the **central region**.
- **Tau leptons** from the same CP-odd higgs, \( a \) are **collimated**!
Tau Lepton’s decay branching ratio

- $\text{Br}(\tau \rightarrow \text{hadronic } \tau + \nu) = 65\%$
  (1 or 3 prong taujet)
- $\text{Br}(\tau \rightarrow \muon + \nu\nu) = 17\%$

In order to get highest cross section with clean signal

We focus on the decay chain

$h \rightarrow 2a \rightarrow 4\tau \rightarrow 2\mu 2\text{ hadronic tau (taujet)}$

When hadronic tau and muon are collimated, we get,

$\pi^0, \pi^-, \pi^+, \mu^-$

Q: How to ID the taujets and muons?

A: Muon - Spectrometer Taujet – on next pages!
Default Hadronic Tau Reconstruction

HADRONIC TAU
Calorimeter seed reconstruction algorithm

- Seeded by a $E_T > 10$ GeV topological jets of cone size 0.4.
- **Tracks within $\Delta R < 0.3$ are associated.**
- Energy calculated from energy in topological jets, with MC correction.
- Direction($\eta$, $\phi$) from energy weighted barycenter of jet with corrections from the associated tracks.
- Charge come from the sum of tracks.
- TauID variables for multivariate technique (likelihood technique) to select signals + reject backgrounds (like QCD).
Expected Performance of tauID

For a loose tauID with efficiency = 60%, rejection = 1 \rightarrow fake rate = 50%
medium tauID (eff = 50%, fake rate = 30%) tight tauID (eff = 30%, fake rate = 5%)

However, it was stated in previous page that, for ATLAS tau reconstruction algorithm,
"Tracks within $\Delta R < 0.3$ are associated"! But NMSSM $dR(\tau,\mu) < 0.3$!
Which means 1 or 3 prong taujet $\rightarrow$ 2 or 4 prong taujet for NMSSM taujet
and ATLAS tauID requires 1 or 3 prong taujet only!

So, an exclusive NMSSM hadronic tau reconstruction algorithm was developed!
Exclusive NMSSM Hadronic Tau Reconstruction

HADRONIC TAU
Motivation

- Existence of muon is disturbing the reconstruction of taujet. It causes inaccuracy in taujet kinematics especially direction.
- Allowing us to use opposite charge requirement for muon-taujet pair.
- Collinear method is sensitive to kinematics of taujets (and muons).

Method

- At first, we search for good muon candidates.
- Then subtract the muon’s track from all the tracks within the event.
- Reconstruct taujet using the remaining tracks.
- Re-calculate all TauID variables.

\[
\begin{align*}
  x_1 &= R_{em} = \frac{\sum_j E_j^{cell} dR}{\sum_j E_j^{cell}} \\
  x_2 &= ISO = \frac{E_T^{EM} + E_T^{Had}}{E_T^{EM} + E_T^{Had}}_{0.1<dR<0.2} \\
  x_3 &= \frac{E_T}{P_T}^{leading track} \\
  x_4 &= \frac{E_T^{EM}}{\sum P_T^{tracks}}
\end{align*}
\]
Performance

Variables depending on track are changed after reprocess, while those depending on calorimeter are almost unaltered. The new taujet has distribution near to $Z \rightarrow \tau \tau$. 

2011/1/14
Acceptance of event Default and Exclusive

<table>
<thead>
<tr>
<th>Selection cuts</th>
<th>(100,4)</th>
<th>(100,5)</th>
<th>(100,8)</th>
<th>(120,4)</th>
<th>(120,5)</th>
<th>(120,8)</th>
<th>$b\bar{b}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>24448</td>
<td>118409</td>
<td>24367</td>
<td>24633</td>
<td>24347</td>
<td>24418</td>
<td>1970844</td>
</tr>
<tr>
<td>$2\mu$</td>
<td>3292</td>
<td>14830</td>
<td>2829</td>
<td>4439</td>
<td>3960</td>
<td>3651</td>
<td>115063</td>
</tr>
<tr>
<td>$2\tau_h$</td>
<td>207</td>
<td>712</td>
<td>136</td>
<td>253</td>
<td>213</td>
<td>211</td>
<td>1155</td>
</tr>
<tr>
<td>$\Delta R &lt; 0.3$ pairs</td>
<td>32</td>
<td>80</td>
<td>8</td>
<td>36</td>
<td>23</td>
<td>26</td>
<td>237</td>
</tr>
<tr>
<td>Opposite Sign ($\mu,\tau$)</td>
<td>4</td>
<td>12</td>
<td>3</td>
<td>3</td>
<td>5</td>
<td>22</td>
<td>25</td>
</tr>
<tr>
<td>Total</td>
<td>24448</td>
<td>118409</td>
<td>24367</td>
<td>24633</td>
<td>24347</td>
<td>24418</td>
<td>1970844</td>
</tr>
<tr>
<td>$2\mu$</td>
<td>3292</td>
<td>14830</td>
<td>2829</td>
<td>4439</td>
<td>3960</td>
<td>3651</td>
<td>115063</td>
</tr>
<tr>
<td>$2\tau_h$</td>
<td>585</td>
<td>2080</td>
<td>290</td>
<td>912</td>
<td>648</td>
<td>454</td>
<td>861</td>
</tr>
<tr>
<td>$\Delta R &lt; 0.3$ pairs</td>
<td>244</td>
<td>739</td>
<td>70</td>
<td>431</td>
<td>272</td>
<td>119</td>
<td>155</td>
</tr>
<tr>
<td>Opposite Sign ($\mu,\tau$)</td>
<td>238</td>
<td>707</td>
<td>68</td>
<td>412</td>
<td>263</td>
<td>116</td>
<td>85</td>
</tr>
<tr>
<td>Increase in acceptance</td>
<td>59.5</td>
<td>58.9</td>
<td>22.7</td>
<td>137</td>
<td>52.6</td>
<td>5.3</td>
<td>3.4</td>
</tr>
</tbody>
</table>

Averagely 50 times more higher acceptance!

~3 times increase in QCD, but it can be suppressed by using other selection cuts.
Event selection and background estimation

PHYSICS ANALYSIS
Signal and background are studied using full simulation data → GEANT4 simulation with detector response at ATLAS

<table>
<thead>
<tr>
<th>Signal</th>
<th>Event Generator</th>
<th>Cross section (fb)</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>NMSSM VBF Higgs</td>
<td>Pythia, Madgraph</td>
<td>56.5</td>
<td>118k</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Main Background</th>
<th>Event Generator</th>
<th>NLO Cross section (pb)</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>ttbar</td>
<td>MC@NLO</td>
<td>81</td>
<td>155k</td>
</tr>
<tr>
<td>bbbar</td>
<td>Pythia</td>
<td>88214</td>
<td>1971k</td>
</tr>
<tr>
<td>ccbar</td>
<td>Pythia</td>
<td>41076</td>
<td>923k</td>
</tr>
</tbody>
</table>

Examples of background from QCD. When the D mesons are misidentified as taujets, they mimic the VBF topology. However, they are reducible backgrounds.

\( m_h = 100 \text{ GeV} \)
\( m_a = 5 \text{ GeV} \)
\( @ 7\text{TeV} \)
Event selection

- **Cut based** method is used to select candidate event. Mainly divided into **3 categories**;
- **Event topology**
  - $2\mu2\tau$jet, $\geq 2$jets, centrality
- **VBF Jet topology**
  - Opposite hemisphere, eta gap, etc......
- **Higgs decay products’ kinematics**
  - Large Missing ET, $\Delta R<0.3$ pairs, Opposite sign, etc......
Limited MC statistics + high rejection rate for QCD
→ Cannot estimate background rate at the end of the cut table.
Background estimation

Easiest solution → Create more MC samples

So how??

Develop new methods for background estimation

1. Cut factorization (possible to estimate the BG rate near the end of table)
2. QCD normalization (QCD’s cross section is hard to be predicted)

Sounds easy but not practical.
QCD production rate
Data >> MC
1. Cut factorization method

We have to assume that there is no correlation between the “Jet kinematics cuts” and “Tau decay products cut”.

Jet Kinematics Cuts
- $j_1\_\eta \times j_2\_\eta < 0$
- Rapidity Gap
- B-jet Veto
- $M_{jj} > 500$ GeV
- Central Jet Veto

Tau Decay Products Cuts
- $MET > 25$ GeV
- $Z$ veto
- $dR < 0.3$ pairs
- Opposite Signs
- $0 < x_{vis} < 1$
- $\cos(|\Delta \phi|) < 0.95$
- Higgs mass window

Basic Cuts
- 2 muons 2 taujets
- At least 2 jets
- Centrality

MC

result

result

result
<table>
<thead>
<tr>
<th>Cut</th>
<th>VBF</th>
<th>$t\bar{t}$</th>
<th>$b\bar{b}$</th>
<th>$c\bar{c}$</th>
<th>$Z \rightarrow \mu\mu$</th>
<th>SUM BG$^1$</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Event</td>
<td>7.60</td>
<td>2819</td>
<td>$3.10 \times 10^6$</td>
<td>$1.36 \times 10^6$</td>
<td>$29.0 \times 10^3$</td>
<td>$4.48 \times 10^6$</td>
<td>322965</td>
</tr>
<tr>
<td>Event Filter</td>
<td>0.34</td>
<td>257.9</td>
<td>$210 \times 10^3$</td>
<td>$93.9 \times 10^3$</td>
<td>3527</td>
<td>$308 \times 10^3$</td>
<td>295041</td>
</tr>
<tr>
<td>Dimuon Trigger</td>
<td>0.21</td>
<td>161.7</td>
<td>$125 \times 10^3$</td>
<td>$56.6 \times 10^3$</td>
<td>2391</td>
<td>$184 \times 10^3$</td>
<td>127081</td>
</tr>
<tr>
<td>VxPrimary</td>
<td>0.21</td>
<td>159.9</td>
<td>$124 \times 10^3$</td>
<td>$56.0 \times 10^3$</td>
<td>2373</td>
<td>$182 \times 10^3$</td>
<td>126172</td>
</tr>
<tr>
<td>Event cleaning</td>
<td>0.20</td>
<td>159.4</td>
<td>$124 \times 10^3$</td>
<td>$56.0 \times 10^3$</td>
<td>2353</td>
<td>$182 \times 10^3$</td>
<td>126606</td>
</tr>
<tr>
<td>$2\mu\tau$</td>
<td>0.02</td>
<td>7.1</td>
<td>859</td>
<td>351</td>
<td>12.2</td>
<td>1230</td>
<td>662</td>
</tr>
<tr>
<td>At least 2 jet Centrality</td>
<td>0.01</td>
<td>5.5</td>
<td>229</td>
<td>106</td>
<td>0.9</td>
<td>342</td>
<td>199</td>
</tr>
<tr>
<td>Central Jet Veto</td>
<td>0.006</td>
<td>0.5</td>
<td>39.3</td>
<td>22.0</td>
<td>0</td>
<td>62.7</td>
<td>29</td>
</tr>
<tr>
<td>$\eta_{j_1} \times \eta_{j_2} &lt; 0$</td>
<td>0.005</td>
<td>0.4</td>
<td>34.6</td>
<td>17.6</td>
<td>0</td>
<td>52.6</td>
<td>27</td>
</tr>
<tr>
<td>$</td>
<td>\eta_{j_1} - \eta_{j_2}</td>
<td>&gt; 3.6$</td>
<td>0.003</td>
<td>0.07</td>
<td>14.1</td>
<td>10.3</td>
<td>0</td>
</tr>
<tr>
<td>B-jet Veto</td>
<td>0.003</td>
<td>0.05</td>
<td>12.6</td>
<td>10.3</td>
<td>0</td>
<td>22.9</td>
<td>9</td>
</tr>
<tr>
<td>$M_{jj} &gt; 500$GeV</td>
<td>0.002</td>
<td>0.02</td>
<td>1.6</td>
<td>4.4</td>
<td>0</td>
<td>6.0</td>
<td>2</td>
</tr>
<tr>
<td>Central Jet Veto</td>
<td>0.002</td>
<td>&lt; 0.02</td>
<td>1.6</td>
<td>2.9</td>
<td>0</td>
<td>4.5</td>
<td>1</td>
</tr>
<tr>
<td>MET &gt; 25 GeV</td>
<td>0.002</td>
<td>0</td>
<td>0.3</td>
<td>0.3</td>
<td>0</td>
<td>0.7</td>
<td>0</td>
</tr>
<tr>
<td>$Z$ veto</td>
<td>0.002</td>
<td>0</td>
<td>0.3</td>
<td>0.3</td>
<td>0</td>
<td>0.7</td>
<td>0</td>
</tr>
<tr>
<td>$\Delta R &lt; 0.3$ pairs</td>
<td>0.001</td>
<td>0</td>
<td>0.05</td>
<td>0.1</td>
<td>0</td>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>Opposite Signs</td>
<td>0.001</td>
<td>0</td>
<td>0.03</td>
<td>0.05</td>
<td>0</td>
<td>0.08</td>
<td>0</td>
</tr>
<tr>
<td>$0 &lt; x_{vis1}, x_{vis2} &lt; 1$</td>
<td>0.001</td>
<td>0</td>
<td>0.03</td>
<td>0.05</td>
<td>0</td>
<td>0.08</td>
<td>0</td>
</tr>
<tr>
<td>$</td>
<td>\cos \Delta \phi</td>
<td>&lt; 0.95$</td>
<td>0.001</td>
<td>0</td>
<td>0.03</td>
<td>0.05</td>
<td>0</td>
</tr>
<tr>
<td>H100 mass window</td>
<td>0.001</td>
<td>0</td>
<td>&lt; 0.02</td>
<td>&lt; 0.02</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>H120 mass window</td>
<td>0</td>
<td>0</td>
<td>&lt; 0.02</td>
<td>&lt; 0.02</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Cut table for 34.8 $pb^{-1}$ @ 7 TeV

Note that there is a discrepancy in between MC and Data; The event numbers at **Centrality (QCD is dominant here)** are used for the next method → QCD normalization.
2. QCD Normalization method

QCD process cross section is hard to be predicted especially for heavy flavor quarks. However, we can make use of the distribution shape from MC and compare it with the experimental data → Normalize to data and get the value of cross section. (Control region = QCD dominant region. Normalize to Control region)

Applying this correction to sample’s cross section.

Figure 9.2: Transverse momentum of the first and second muon. The shape of the distribution is well described by the MC sample.
Systematic errors

- Measurement of the luminosity (11%)
- Resolution uncertainty in electron (2%)
- Resolution uncertainty in muon (2%)
- Resolution uncertainty in hadronic $\tau$ (5%)
- Jet energy scale (20%)

- Theoretical uncertainty (6% for $ttbar$, 1% for signal)
- Scale uncertainty of the sample (5% for $ttbar$)

- Cut factorization method (35%)
- QCD normalization method (24%)

Depending on the analysis, the systematic error is between 32% - 47%.
VBF Exclusive Analysis for 34.8 pb$^{-1}$ @ 7 TeV

PHYSICS ANALYSIS
The results are consistent within errors.

\[ \text{Expected} = 2.2 \pm 1.7 \]

\[ \text{Observed} = 1 \]

The results are consistent within errors.
Sensitivity study for 5 fb\(^{-1}\) @ 7 TeV and 30 - 150 fb\(^{-1}\) @ 14 TeV

PHYSICS ANALYSIS
Sensitivity of NMSSM Higgs to four taus search with data of 5 fb^{-1} @ 7 TeV

Without mass window cut, at most 0.4 event! But perhaps 1 event pop up? But it also means we will not discover anything! No way! We can change the strategy from exclusive VBF study to inclusive study. Will be shown at the last section.

<table>
<thead>
<tr>
<th>Cut</th>
<th>$tt$</th>
<th>$bb$</th>
<th>$cc$</th>
<th>(120,4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Event</td>
<td>$405 \times 10^3$</td>
<td>$202.9 \times 10^6$</td>
<td>$94.5 \times 10^6$</td>
<td>231</td>
</tr>
<tr>
<td>Event Filter</td>
<td>$37.1 \times 10^3$</td>
<td>$13.8 \times 10^6$</td>
<td>$6.54 \times 10^6$</td>
<td>52.5</td>
</tr>
<tr>
<td>Dimuon Trigger</td>
<td>$23.2 \times 10^3$</td>
<td>$8.19 \times 10^6$</td>
<td>$3.94 \times 10^6$</td>
<td>34.0</td>
</tr>
<tr>
<td>VxPrimary</td>
<td>$23.0 \times 10^3$</td>
<td>$8.10 \times 10^6$</td>
<td>$3.90 \times 10^6$</td>
<td>33.5</td>
</tr>
<tr>
<td>Event cleaning</td>
<td>$22.9 \times 10^3$</td>
<td>$8.10 \times 10^6$</td>
<td>$3.90 \times 10^6$</td>
<td>33.5</td>
</tr>
<tr>
<td>$2\mu 2\tau$</td>
<td>$1022$</td>
<td>$56.3 \times 10^3$</td>
<td>$24.5 \times 10^3$</td>
<td>5.7</td>
</tr>
<tr>
<td>At least 2 jet Centrality</td>
<td>$789$</td>
<td>$15.0 \times 10^3$</td>
<td>$7369$</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>$65.3$</td>
<td>$2574$</td>
<td>$1535$</td>
<td>1.5</td>
</tr>
<tr>
<td>$\eta_{j1} \times \eta_{j2} &lt; 0$</td>
<td>$60.1$</td>
<td>$2265$</td>
<td>$1228$</td>
<td>1.4</td>
</tr>
<tr>
<td>$</td>
<td>\eta_{j1} - \eta_{j2}</td>
<td>&gt; 3.6$</td>
<td>$10.5$</td>
<td>$927$</td>
</tr>
<tr>
<td>B-jet Veto</td>
<td>$7.8$</td>
<td>$824$</td>
<td>$716.5$</td>
<td>1.0</td>
</tr>
<tr>
<td>$M_{jj} &gt; 500GeV$</td>
<td>$2.6$</td>
<td>$103$</td>
<td>$307.1$</td>
<td>0.7</td>
</tr>
<tr>
<td>Central Jet Veto</td>
<td>$&lt; 2.6$</td>
<td>$103$</td>
<td>$204.7$</td>
<td>0.6</td>
</tr>
<tr>
<td>MET &gt; 25GeV</td>
<td>$&lt; 2.2$</td>
<td>$21.2$</td>
<td>$23.9$</td>
<td>0.5</td>
</tr>
<tr>
<td>Z veto</td>
<td>$&lt; 2.1$</td>
<td>$21.2$</td>
<td>$23.9$</td>
<td>0.5</td>
</tr>
<tr>
<td>$\Delta R &lt; 0.3$ pairs</td>
<td>$&lt; 0.04$</td>
<td>$3.0$</td>
<td>$6.8$</td>
<td>0.4</td>
</tr>
<tr>
<td>Opposite Signs</td>
<td>$0$</td>
<td>$2.0$</td>
<td>$3.4$</td>
<td>0.4</td>
</tr>
<tr>
<td>$0 &lt; x_{vtx1}, x_{vtx2} &lt; 1$</td>
<td>$0$</td>
<td>$2.0$</td>
<td>$3.4$</td>
<td>0.4</td>
</tr>
<tr>
<td>$</td>
<td>\cos \Delta \phi</td>
<td>&lt; 0.95$</td>
<td>$0$</td>
<td>$2.0$</td>
</tr>
<tr>
<td>H100 mass window</td>
<td>$0$</td>
<td>$&lt; 1.0$</td>
<td>$&lt; 3.2$</td>
<td>0.3</td>
</tr>
<tr>
<td>H120 mass window</td>
<td>$0$</td>
<td>$&lt; 1.0$</td>
<td>$&lt; 3.2$</td>
<td>0.3</td>
</tr>
</tbody>
</table>

$m_h = 120$ GeV  
$m_a = 4$ GeV
Sensitivity of NMSSM Higgs to four taus search with data of 30 fb\(^{-1}\) @ 14 TeV

<table>
<thead>
<tr>
<th>Cut</th>
<th>VBF</th>
<th>(\ell\ell)</th>
<th>(bb)</th>
<th>(cc)</th>
<th>SUM BG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Event</td>
<td>4728</td>
<td>(2.32 \times 10^6)</td>
<td>(3.45 \times 10^9)</td>
<td>(1.68 \times 10^9)</td>
<td>(5.15 \times 10^9)</td>
</tr>
<tr>
<td>Event Filter</td>
<td>1075</td>
<td>(2.12 \times 10^6)</td>
<td>(2.34 \times 10^6)</td>
<td>(1.16 \times 10^6)</td>
<td>(3.52 \times 10^6)</td>
</tr>
<tr>
<td>Dimuon Trigger</td>
<td>696</td>
<td>(1.33 \times 10^6)</td>
<td>(1.39 \times 10^6)</td>
<td>(7.00 \times 10^6)</td>
<td>(2.11 \times 10^6)</td>
</tr>
<tr>
<td>Vx Primary</td>
<td>686</td>
<td>(1.32 \times 10^6)</td>
<td>(1.38 \times 10^6)</td>
<td>(6.92 \times 10^6)</td>
<td>(2.08 \times 10^6)</td>
</tr>
<tr>
<td>Event cleaning</td>
<td>685</td>
<td>(1.31 \times 10^6)</td>
<td>(1.38 \times 10^6)</td>
<td>(6.92 \times 10^6)</td>
<td>(2.08 \times 10^6)</td>
</tr>
</tbody>
</table>

**Highest sensitivity**

\(VBF\)

\(m_h = 120\) GeV

\(m_a = 4\) GeV

**Conservative case**

BG = 78 \(\pm 86\)

**Optimistic case**

BG = 0.8 \(\pm 0.7\)

- very loose tau ID used.

Can improve rejection rate \(\sim 10\) while keeping the efficiency.

2 taujets \(\rightarrow\) 77.7/100 \(\sim 0.8\)

- Due to limited MC samples

\(\rightarrow\) Errors are dominated by statistical error. Possible to reduce at least 50% in the future.

Signal = 6.9 \(\pm 1.2\)

BG = 0.8 \(\pm 0.6\) (with errors + 50% MC stat. error)

Significance = 4.6 (without errors), 4.1 (optimistic)
Sensitivity of NMSSM Higgs to four taus search with data of 30 - 150 fb\(^{-1}\) @ 14 TeV

We can either wait for 130 fb\(^{-1}\) of data or try to reduce statistical and systematic errors for earlier discovery!
Inclusive Analysis for $34.8 \text{ pb}^{-1} @ 7 \text{ TeV}$

(Gluon-Gluon Fusion + VBF)

PHYSICS ANALYSIS
Vector Boson Fusion (VBF) process’s cross section is quite low (~pb) \(\rightarrow\) Instead of waiting for years of data for exclusive analysis, we perform inclusive analysis as well, removing VBF’s selection cuts which are very tight now. Gluon fusion now has the highest sensitivity.

\[
\begin{array}{|c|c|c|c|c|c|c|c|}
\hline
\text{Cut} & \text{GGF} & \text{tt} & \text{bb} & \text{cc} & \text{Z} \rightarrow \mu\mu & \text{SUM BG} & \text{Data} \\
\hline
\text{Total Event} & 16.1 & 2819 & 1.41 \times 10^6 & 657.5 \times 10^3 & 29.0 \times 10^3 & 2.10 \times 10^6 & 322965 \\
\text{Event Filter} & 3.0 & 257.9 & 95.7 \times 10^3 & 45.5 \times 10^3 & 3526 & 145.0 \times 10^3 & 295041 \\
\text{Dimuon Trigger} & 2.0 & 161.7 & 57.0 \times 10^3 & 27.4 \times 10^3 & 2391 & 87.0 \times 10^3 & 127081 \\
\text{VxFPrimary} & 2.0 & 159.9 & 56.4 \times 10^3 & 27.1 \times 10^3 & 2372 & 86.0 \times 10^3 & 126172 \\
\text{Event cleaning} & 2.0 & 159.4 & 56.3 \times 10^3 & 27.1 \times 10^3 & 2354 & 86.0 \times 10^3 & 126606 \\
\hline
\end{array}
\]

Table 9.25: Cut table for inclusive study using data 2010. (34.8 pb\(^{-1}\)) NMSSM Higgs boson with mass (120,4) produced via gluon fusion is on the left row for comparison.

\[\text{Expected} = 2.1 \pm 1.2(\text{stat.}) \pm 0.7(\text{sys.})\]

\[\text{Observed} = 3\]

The result is again consistent within errors
Summary and prospects

• Light $a$ scenario of NMSSM was studied but default taujet reconstruction algorithm + TauID in ATLAS has very low acceptance for the signal.

• A new taujet reconstruction algorithm was developed exclusively for NMSSM taujet. An improvement of factor of 50 in acceptance can be achieved using this algorithm.

By using NMSSM exclusive taujet reconstruction algorithm;

• No significant excesses were found for both exclusive and inclusive analyses for 34.8 pb$^{-1}$ of data at 7 TeV.

• Sensitivities of NMSSM Higgs at 7 TeV and 14 TeV were studied.

• Data with 5fb$^{-1}$ at 7 TeV might provide a hint for the existence of NMSSM Higgs, and for optimistic case, data with 50 fb$^{-1}$ at 14 TeV could possibly claim the discovery of $m_h = 120$ GeV and $m_a = 4$ GeV NMSSM higgs if they do exist.
Event Display
BACKUP
## 2010 Proton Run: Performance highlight

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak stable luminosity delivered</td>
<td>$2.07 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$</td>
</tr>
<tr>
<td>Maximum luminosity delivered in one fill</td>
<td>6.3 pb$^{-1}$</td>
</tr>
<tr>
<td>Maximum luminosity delivered in one day</td>
<td>6 pb$^{-1}$</td>
</tr>
<tr>
<td>Maximum luminosity delivered in 7 days</td>
<td>25 pb$^{-1}$</td>
</tr>
<tr>
<td>Total integrated luminosity</td>
<td>50 pb$^{-1}$</td>
</tr>
<tr>
<td>Maximum bunches per beam</td>
<td>368</td>
</tr>
<tr>
<td>Maximum colliding bunches</td>
<td>348</td>
</tr>
<tr>
<td>Maximum average events per bunch crossing</td>
<td>3.8</td>
</tr>
<tr>
<td>Longest time in Stable Beams for one fill</td>
<td>30.3 hours</td>
</tr>
<tr>
<td>Longest time in Stable Beams for 7 days</td>
<td>69.9 hours (41.6%)</td>
</tr>
<tr>
<td>Fastest turnaround to Stable Beams</td>
<td>3.7 hours (protons)</td>
</tr>
</tbody>
</table>
A summary of ATLAS detector

- **Inner Detector**
  - $|\eta|<2.5$, solenoid $B=2T$
  - Si Pixels, Si strips, TRT
  - Tracking and vertexing
  - $e/\pi$ separation
  - Resolution: $\sigma/p_T \sim 3.8 \times 10^{-4} p_T [GeV] \oplus 0.015$

- **EM calorimeter**
  - $|\eta|<3.2$
  - LAr/Pb accordion structure $e/\gamma$ trigger, id + measurement
  - E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

- **HAD calorimeter**
  - $|\eta|<3.2$ (Forward Calo. $|\eta|<4.8$)
  - Scint./Fe tiles in the central, W(Cu)/LAr in fwd region
  - Trigger, jets + missing Et
  - E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

- **Muon Spectrometer**
  - $|\eta|<2.7$
  - Toroid B-Field
  - Muon Momentum resolution $<10\%$ up to $\sim 1$ TeV
Inner Tracker ($|\eta|<2.5$)

**Semiconductor Tracker (SCT)**
- Silicon strip detector
- Barrel: 4 cylindrical layers
- End-cap: 9 disks per side

**Pixel Detector**
- Hybrid silicon pixel detector
- Barrel: innermost cylindrical layer and 2 outer cylindrical layers
- End-cap: 3 disks per side

**Transition Radiation Tracker (TRT)**
- Straw-tube tracking chamber with transition radiation capability.
- Straws run in axial direction in barrel and radial direction in end-caps.
Electromagnetic Calorimeter

- **Pb/Lar sampling calorimeter** with accordion-shaped electrodes
- **Three longitudinal segmentation**
- **Cell size in $\Delta \eta \times \Delta \phi$**
  - 1st (strip) : $0.003 \times 0.1$, 2nd (middle) : $0.025 \times 0.025$, 3rd (back) : $0.05 \times 0.025$
- **Pre-sampling in front** of calorimeter in $|\eta| < 1.8$ : $\Delta \eta \times \Delta \phi \sim 0.025 \times 0.1$
Hadronic Calorimeter

Barrel Fe + Tile fiber, $11\lambda$, $|\eta|<1.7$, 0.1x0.1 (DAQ=0.3) Tower (3 Layers)

Endcap Cu+LAr, $14\lambda$, $|\eta|=1.5-3.2$, 0.1x0.1 for $|\eta|=1.5-2.5$, 0.2x0.2 for $|\eta|=2.5-3.2$, 4 Layers

Forward Cu+W+W 3 Layers
LAr 0.5mm gap $10\lambda$
$|\eta|=3.1-4.9$ 0.2x0.2
# Performance of ATLAS Detectors

<table>
<thead>
<tr>
<th>ATLAS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic field</td>
<td>2 T solenoid + toroid</td>
</tr>
<tr>
<td></td>
<td>(0.5 T barrel; 1 T end-cap)</td>
</tr>
<tr>
<td>Tracker</td>
<td>Si pixels and strips + TRT</td>
</tr>
<tr>
<td></td>
<td>$\sigma/p_T \approx 5 \times 10^{-4} p_T + 0.01$</td>
</tr>
<tr>
<td>EM calorimeter</td>
<td>LAr + Pb</td>
</tr>
<tr>
<td></td>
<td>$\sigma/E \approx 10%/\sqrt{E} \oplus 0.007$</td>
</tr>
<tr>
<td>Hadronic calorimeter</td>
<td>Scint. + Fe / LAr + Cu (10 $\lambda$)</td>
</tr>
<tr>
<td></td>
<td>$\sigma/E \approx 50%/\sqrt{E} \oplus 0.03$ GeV</td>
</tr>
<tr>
<td>Muon spectrometer</td>
<td>$\sigma/p_T \approx 2% @ 50$ GeV -</td>
</tr>
<tr>
<td></td>
<td>10% @ 1 TeV (ID + MS)</td>
</tr>
</tbody>
</table>

Electron/γ Reconstruction

- Leakage into Hadronic calorimeter
- Calorimeter shower shapes in 2nd sampling
  - Shower shape in η and φ
  - Energy-weighted lateral width
- Calorimeter shower shapes in 1st sampling
  - Details of energy deposition structure in cells
  - Shower width
- Track quality
  - Number of hits in pixel, SCT, TRT
  - Transverse impact parameter
- Track-cluster matching
  - Δη × Δφ position matching at calorimeter, E/p

Red : Calorimeter-related
Blue : ID-related
Green : track-cluster

Fake rate < 0.1%
Muon Reconstruction

Keywords: Hits, Track, $E_{\text{loss}}$, Inner, Tag
Standalone, Combined, Tagged Muon

Efficiency ~ 90% (Pt>10GeV), fake rate~0.01%, Pt resolution~2%-4%
Hadronic Tau Reconstruction

• Main decay modes of Tau Lepton
  \[ \tau^- \rightarrow l^- \nu_\tau \bar{\nu}_l \quad \sim 35\% \]
  \[ \tau^- \rightarrow \nu_\tau \pi^- + N\pi^0 \quad \sim 45\% \]
  \[ \tau^- \rightarrow \nu_\tau \pi^- \pi^+ \pi^- + N\pi^0 \quad \sim 10\% \]

• Characteristic of Taujet
  1. One or Three Charged Tracks
  2. Pions are boosted → narrow signal cone

• Hadronic Taus are Identified using the facts above.

• There are 2 ways:
  A) Track-base
  B) Calo-base

Eff~70%, Fake~50%
for this analysis
Higgs Production

Gluon Fusion  Vector Boson Fusion  Associative Production with W, Z  Associative Production with top, bottom

Typical cross section (SM) is about 3 picobarn (pb) for Vector Boson Fusion (VBF)

For NMSSM, some corrections are needed. $\rightarrow \sigma=2.9\text{pb} @ 10\text{TeV}$ (~SM)

Higgs Production Cross Section (SM)
## Systematic errors (cut factorization)

<table>
<thead>
<tr>
<th>Event Selection</th>
<th>(100,4)</th>
<th>(100,5)</th>
<th>(100,8)</th>
<th>(120,4)</th>
<th>(120,5)</th>
<th>(120,8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total event</td>
<td>24448</td>
<td>118409</td>
<td>24367</td>
<td>24633</td>
<td>24347</td>
<td>24418</td>
</tr>
<tr>
<td>Event Filter</td>
<td>4209</td>
<td>18928</td>
<td>3501</td>
<td>5601</td>
<td>4982</td>
<td>4462</td>
</tr>
<tr>
<td>Dimuon Trigger</td>
<td>2700</td>
<td>12927</td>
<td>2255</td>
<td>3624</td>
<td>3243</td>
<td>2855</td>
</tr>
<tr>
<td>VxPrimary</td>
<td>2669</td>
<td>12146</td>
<td>2237</td>
<td>3574</td>
<td>3199</td>
<td>2818</td>
</tr>
<tr>
<td>Event Cleaning</td>
<td>2661</td>
<td>12120</td>
<td>2230</td>
<td>3567</td>
<td>3192</td>
<td>2810</td>
</tr>
<tr>
<td>$2\mu,2\tau$</td>
<td>399</td>
<td>1425</td>
<td>194</td>
<td>611</td>
<td>432</td>
<td>297</td>
</tr>
<tr>
<td>At least 2 jet</td>
<td>218</td>
<td>764</td>
<td>108</td>
<td>340</td>
<td>225</td>
<td>145</td>
</tr>
<tr>
<td>Centrality</td>
<td>108</td>
<td>354</td>
<td>34</td>
<td>163</td>
<td>117</td>
<td>74</td>
</tr>
<tr>
<td>$\eta_{j1} \times \eta_{j2} &lt; 0$</td>
<td>99</td>
<td>306</td>
<td>33</td>
<td>154</td>
<td>102</td>
<td>63</td>
</tr>
<tr>
<td>$</td>
<td>\eta_{j1} - \eta_{j2}</td>
<td>&gt; 3.6$</td>
<td>68</td>
<td>195</td>
<td>27</td>
<td>115</td>
</tr>
<tr>
<td>B-jet Veto</td>
<td>67</td>
<td>187</td>
<td>27</td>
<td>111</td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td>$M_{jj} &gt; 500\text{GeV}$</td>
<td>53</td>
<td>155</td>
<td>24</td>
<td>77</td>
<td>47</td>
<td>29</td>
</tr>
<tr>
<td>Central Jet Veto</td>
<td>38</td>
<td>111</td>
<td>21</td>
<td>60</td>
<td>39</td>
<td>22</td>
</tr>
<tr>
<td>MET $&gt; 25\text{GeV}$</td>
<td>32(29.2)</td>
<td>97(91.6)</td>
<td>19(17.3)</td>
<td>49(43.4)</td>
<td>34(31.3)</td>
<td>17(15.2)</td>
</tr>
<tr>
<td>$Z$ veto</td>
<td>32(29.2)</td>
<td>97(91.6)</td>
<td>19(17.3)</td>
<td>49(43.4)</td>
<td>34(31.3)</td>
<td>17(15.2)</td>
</tr>
<tr>
<td>$\Delta R &lt; 0.3$ pairs</td>
<td>27(25.7)</td>
<td>85(74.3)</td>
<td>15(11.1)</td>
<td>44(37.2)</td>
<td>29(27.3)</td>
<td>14(10.1)</td>
</tr>
<tr>
<td>Opposite Sign</td>
<td>27(25.3)</td>
<td>83(71.5)</td>
<td>15(11.1)</td>
<td>41(35.3)</td>
<td>29(27.0)</td>
<td>14(10.1)</td>
</tr>
<tr>
<td>$0 &lt; x_{vis1}, x_{vis2} &lt; 1$</td>
<td>21(21.8)</td>
<td>72(62.4)</td>
<td>14(10.5)</td>
<td>40(33.9)</td>
<td>28(24.7)</td>
<td>14(9.8)</td>
</tr>
<tr>
<td>$</td>
<td>\cos \Delta \phi</td>
<td>&lt; 0.95$</td>
<td>21(21.8)</td>
<td>68(57.7)</td>
<td>11(8.0)</td>
<td>39(31.3)</td>
</tr>
<tr>
<td>H100 mass window</td>
<td>20(20.4)</td>
<td>65(55.5)</td>
<td>11(7.4)</td>
<td>29(23.2)</td>
<td>18(17.7)</td>
<td>11(8.0)</td>
</tr>
<tr>
<td>H120 mass window</td>
<td>5(6.0)</td>
<td>10(13.5)</td>
<td>2(1.9)</td>
<td>36(30.2)</td>
<td>22(20.3)</td>
<td>12(8.6)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mass points</th>
<th>(100,4)</th>
<th>(100,5)</th>
<th>(100,8)</th>
<th>(120,4)</th>
<th>(120,5)</th>
<th>(120,8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H100 mass window</td>
<td>+2.0</td>
<td>-14.6</td>
<td>-32.7</td>
<td>-20</td>
<td>-1.7</td>
<td>-27.3</td>
</tr>
<tr>
<td>H120 mass window</td>
<td>+20.0</td>
<td>+35.0</td>
<td>-5.0</td>
<td>-16.1</td>
<td>-7.7</td>
<td>-28.3</td>
</tr>
</tbody>
</table>
Reconstruction of Higgs mass
-Collinear Approximation-

Assume that, decay products of $a_1$ and $a_2$ are travelling in the same direction. This is confirmed at the truth level.

\[ P_1 = P_{\mu_1} + P_{\tau_1} = x_1 P_{a_1} \]
\[ P_2 = P_{\mu_2} + P_{\tau_2} = x_2 P_{a_2} \]
\[ MET = MET_1 + MET_2 \]
\[ = (1 - x_1) P_{a_1} + (1 - x_2) P_{a_2} \]
\[ m_h = m_{a_1 a_2} \]
\[ = \frac{m_{P_1 P_2}}{\sqrt{x_1 x_2}} \]