Searching for New Physics in Di-Tau Final States with ATLAS

Trevor Vickey

University of Wisconsin, Madison

December 2, 2008

University of Pennsylvania
Experimental High-Energy Physics Seminar
A Beautiful Picture of Nature

We have an extremely successful Standard Model (SM) of particle physics. However, a number of significant pieces are still missing…

Just to name a few:

- Dark Matter
- Dark Energy
- Electroweak Symmetry Breaking
- Quantum Gravity
Could find some answers by looking in di-tau final states

- Many theories beyond the SM predict new physics here

The tau lepton is kind of a heavy cousin of the electron (third generation)

- Massive $\sim1.78$ GeV/c$^2$
- Measurable lifetime $c\tau \sim 87$ $\mu$m
- Decays hadronically $\sim 65\%$ of the time
Electroweak Symmetry Breaking

Higgs Mechanism believed to be responsible for electroweak symmetry breaking

- The Higgs boson has eluded experimentalists for decades
- A key objective for the CERN Large Hadron Collider

For low Higgs masses, tau lepton final states have an advantage over bb

- Good discovery sensitivity in ~30 fb⁻¹ of 14 TeV LHC data

Vector Boson Fusion
Supersymmetry?

Every particle has a “super-partner” particle

- Fermion ↔ Boson

Motivation for Supersymmetry

- Naturalness (Hierarchy Problem)
- Unification of the forces (gauge couplings)
- Provides a candidate for Dark Matter

Minimal Supersymmetric extension to the SM: a two Higgs doublet model (h, A, H, H±)

- Coupling to the tau could be significantly enhanced over the SM
- Some Higgses could be quite massive ~500 GeV
Extra Dimensions? Grand Unification?

Some models predict an extra gauge boson, referred to as the Z’

Would appear as a high mass resonance

- Z’ could couple equally to all generations (inclusiveness)
- Or preferentially to the third (exclusiveness)

The current limit on Z’→tau tau searches comes from the Tevatron

- From CDF > ~400 GeV/c² @ 95% CL

A massive graviton could be another source of di-tau resonances

The main focus of this talk
The Large Hadron Collider (LHC)
One Primary Objective of the LHC
Elucidate the mechanism responsible for Electroweak Symmetry Breaking

- Particle accelerator located at CERN (Geneva, Switzerland)
- 26.7 km circumference
- pp collider at $\sqrt{s} = 14$ TeV
- Instantaneous luminosity of $\sim 10^{33} - 10^{34}$ cm$^{-2}$s$^{-1}$
- 40 MHz bunch-crossings with a “pile-up” of 2-20 inelastic collisions per crossing
- First circulating beam September 10, 2008 / First collisions in 2009 (?)
The Large Hadron Collider

Housed in the former LEP tunnel

- Dipole field at 7 TeV is 8.33 T
- ~350 MJ per beam!
- Ultimately ~2800 bunches
- Vacuum $10^{-13}$ atm (~6500 m$^3$ pumped)
- 1232 Dipoles (operate at 1.9 K)
- 858 Quadrupoles
- Typical store lasts ~10 hours
- Can also be used for ion running (Pb)
- Final price tag estimated at 4G EUR
First circulating beam!

- 450 GeV Beam 1 (clockwise) ~10:30
- 450 GeV Beam 2 (counter-clockwise) ~15:00
September 19, 2008

Electrical fault during powering tests of the main dipole circuit in Sector 3-4

- Resulted in magnet displacements and damage to super-insulating blankets
- Afterwards, it became quite clear that collisions during 2008 would not occur
The ATLAS Experiment
The ATLAS Experiment

A Toroidal LHC ApparatuS (ATLAS)

- Collaboration formed in 1992
- As of April 2007: 37 Countries, 167 Institutions, ~2000 Members
- The largest collider detector ever built
The ATLAS Experiment

General purpose experiment at the LHC

- Not just poised for finding and studying Higgs: Top, Exotics, SUSY, etc.
- Length ~40 m, Radius ~10 m, Weight ~7k tons, Channels ~$10^8$
The ATLAS Experiment

The Inner Tracker

- Comprised of the silicon Pixel Detector (50 x 400 μm), Semiconductor Tracker (silicon strips 80 μm pitch), Transition Radiation Tracker (straw tracker)
- Resides inside of the central solenoid (magnetic field of 2 Tesla)

\[
\frac{\delta p_T}{p_T} \simeq 5 \times 10^{-4} \oplus 0.01
\]
The ATLAS Experiment

Electromagnetic Calorimeter

- Pb and liquid Ar

\[ \frac{\delta E}{E} = \frac{0.1}{\sqrt{E}} \]

Hadronic Calorimeter

- Fe + scintillator and Cu + liquid Ar

\[ \frac{\delta E}{E} = \frac{0.5}{\sqrt{E}} \oplus 0.03 \ |\eta| < 3 \]

\[ \frac{\delta E}{E} = \frac{1}{\sqrt{E}} \oplus 0.07 \ |\eta| \geq 3 \]

Muons

- Monitored Drift-Tube chambers
- Cathode Strip Chambers
- Resistive Plate Chambers
- Thin Gap Chambers

\[ \frac{\delta p_T}{p_T} \simeq 0.1 \text{ at } 1 \text{ TeV} \]
The ATLAS Experiment

Trigger and Data Acquisition System:

- Level-1 is hardware, Level-2 confined to “Regions of Interest”, Event Filter has the ability to access the entire event

- High-Level Trigger

Interaction rate
~1 GHz
Bunch crossing rate 40 MHz

LEVEL 1 TRIGGER
< 75 (100) kHz
< 10 μs

Regions of Interest

LEVEL 2 TRIGGER
~ 1 kHz
~10 ms

EVENT FILTER
~ 100 Hz
~1 s

~100 MB/s
Average Event Size ~2 MB
~1 PB/year (petabyte = 10^{15} bytes!)
September 10, 2008

First beam event in ATLAS!
After September 19, 2008

ATLAS continues taking valuable cosmics data...

- We get a constant delivery of cosmic rays for free
- Typical trigger rate is 1 – 200 Hz
- Useful for alignment studies
- Debug DAQ
- Exercise data-taking chain…
The LHC has ushered in a new era…

- Collisions in 2009 (?)
- Few ~100 pb\(^{-1}\) by the year’s end?
- Both ATLAS and CMS have already recorded beam data!

Understand the detectors…
- Diagnose hot or dead channels
- Tally up dead material
- Tracking detector alignment
- Tune the detector simulations to better match ATLAS and CMS

…do Standard Model measurements
- Examine our standard candles
- Demonstrate the ability to measure Ws, Zs and top quarks (b-jet identification)

…then search for the Higgs and New Physics

### LHC The first five years?

<table>
<thead>
<tr>
<th>Year</th>
<th>Intensity</th>
<th>Cross Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>~100 pb(^{-1})</td>
<td>(10^{31}) cm(^{-2}) s(^{-1})</td>
</tr>
<tr>
<td>2010</td>
<td>~1 fb(^{-1})</td>
<td>(10^{32}) cm(^{-2}) s(^{-1})</td>
</tr>
<tr>
<td>2011</td>
<td>~10 fb(^{-1})</td>
<td>(2 \times 10^{33}) cm(^{-2}) s(^{-1})</td>
</tr>
<tr>
<td>2012</td>
<td>~30 fb(^{-1})</td>
<td>(2 \times 10^{33}) cm(^{-2}) s(^{-1})</td>
</tr>
<tr>
<td>2013</td>
<td>~100 fb(^{-1})</td>
<td>(2 \times 10^{34}) cm(^{-2}) s(^{-1})</td>
</tr>
</tbody>
</table>

1 pb\(^{-1}\) = 3 days at \(10^{31}\) cm\(^{-2}\) s\(^{-1}\)
ATLAS Z’ Studies
Three Final States Considered

Considered four signal mass points (all three di-tau final states: ll, lh, hh)

- 600, 800, 1000 and 2000 GeV
- Used cross-sections from the Sequential Standard Model ("SSM")
- Backgrounds considered: Drell-Yan, QCD di-jets, W+jets, Z+jets, ttbar

Mass distribution from MC Truth
Event Selection (lh final-state)

(a) Trigger
- Trig_EF_e25i || Trig_EF_e60 || Trig_EF_mu20i
- Hadronic tau trigger not yet explored (could be used in combination with MET trigger)

(b) Lepton Selection
- Good electrons and muons as selected by the offline software
- Must have at least one electron or muon for the lh channel
- $|\eta| < 2.5$; $p_T > 27$ (e); $p_T > 22$ (mu)

(c) Hadronic Tau
- Good hadronic taus has selected by the offline software
- Require number of tracks to be 1 || 3
- Tau $p_T > 60$
- Cut on a likelihood variable (derived from a handful of discriminants) as a function of the tau transverse energy (enhances QCD rejection)
Hadronic Tau ID in ATLAS

Hadronic tau identification at a hadron collider is a difficult task

• Complicated by the need to distinguish from QCD multi-jets
• Tau jets have lower track multiplicities contained in a narrow cone
• Characteristics of the track system and the calorimetric showers also help to distinguish against QCD jets (fakes)

Two algorithms in ATLAS: calorimetry-based and track-based:

• Calorimetry-based: Exploit collimated energy deposition, isolation region, EM Radius and Fraction
• Track-based: Exploit track multiplicity, isolation region, impact parameter, invariant mass

In this study the calorimetry-based algorithm was used
Hadronic Tau ID in ATLAS

A one-dimensional likelihood ratio is built from multiple discriminating variables

- Includes discrete variables like number of tracks or tau charge, as well as continuous variables such as the radius of the cluster in the EM calorimeter

We cut on the value of the log of this likelihood ratio (LLH) as a function of $E_T$

- A fixed cut would not be optimal for jet rejection, nor flat as a function of energy
Event Selection (lh final-state)

(d) Opposite Charge
   • Require that the product of the tau and lepton charges be <= 0

(e) Missing Transverse Energy
   • Require MET > 30

(f) Transverse Mass
   • Build the transverse mass using the lepton and MET
   • Require MT < 20

(g) Total Event pT (vector sum)
   • Require pT TOT < 50

(h) Visible Mass
   • Build the visible mass using the lepton, tau and MET four-vector (Pz = 0)
   • Use cuts on Mvis like a mass window, but only with a lower bound

(i) Mass Reconstruction (collinear approximation)
   • Check that the two taus are not back-to-back in the lab frame
   • Cut on the fractions of the visible tau momentum carried by the decay daughters
Results for the lh final-state
Analysis for the lh final-state

Includes all four Z’ signal masses

• Assume 14 TeV running
• ATLAS full detector simulation

<table>
<thead>
<tr>
<th>Cut</th>
<th>(m = 600) GeV</th>
<th>(m = 800) GeV</th>
<th>(m = 1000) GeV</th>
<th>(m = 2000) GeV</th>
<th>(t\bar{t})</th>
<th>W+ jets</th>
<th>Z+ jets</th>
<th>QCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>1356.0</td>
<td>516.8</td>
<td>223.6</td>
<td>11.6</td>
<td>213494.2</td>
<td>12358210.0</td>
<td>2062080.5</td>
<td>3369127.5</td>
</tr>
<tr>
<td>Lepton</td>
<td>905.1</td>
<td>336.2</td>
<td>139.8</td>
<td>6.6</td>
<td>151010.4</td>
<td>9028033.0</td>
<td>1062146.4</td>
<td>121617.1</td>
</tr>
<tr>
<td>Tau</td>
<td>367.6</td>
<td>153.2</td>
<td>67.0</td>
<td>3.6</td>
<td>7808.2</td>
<td>74818.4</td>
<td>39573.5</td>
<td>3354.1</td>
</tr>
<tr>
<td>Charge</td>
<td>314.8</td>
<td>132.1</td>
<td>58.4</td>
<td>3.1</td>
<td>2487.0</td>
<td>3502.8</td>
<td>23097.7</td>
<td>831.4</td>
</tr>
<tr>
<td>(M_{TR} &gt; 30)</td>
<td>269.7</td>
<td>115.7</td>
<td>53.4</td>
<td>2.9</td>
<td>2034.6</td>
<td>2343.8†</td>
<td>707.7</td>
<td>181.8†</td>
</tr>
<tr>
<td>(P_T) TOT &lt; 50</td>
<td>186.7</td>
<td>77.9</td>
<td>35.0</td>
<td>1.7</td>
<td>164.5</td>
<td>182.6†</td>
<td>245.4</td>
<td>86.4†</td>
</tr>
<tr>
<td>(M_{vis} &gt; 300)</td>
<td>165.2</td>
<td>68.0</td>
<td>30.5</td>
<td>1.4</td>
<td>44.6</td>
<td>149.7†</td>
<td>175.7</td>
<td>16.2†</td>
</tr>
<tr>
<td>(M_{col})</td>
<td>144.7</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>17.1</td>
<td>44.5†</td>
<td>18.8</td>
<td>8.9†</td>
</tr>
<tr>
<td>(M_{vis} &gt; 400)</td>
<td>23.5</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>5.7</td>
<td>5.8†</td>
<td>5.0</td>
<td>1.5†</td>
</tr>
<tr>
<td>(M_{col})</td>
<td>–</td>
<td>59.1</td>
<td>–</td>
<td>–</td>
<td>6.9</td>
<td>20.1†</td>
<td>5.0</td>
<td>3.1†</td>
</tr>
<tr>
<td>(M_{vis} &gt; 500)</td>
<td>–</td>
<td>7.8</td>
<td>–</td>
<td>–</td>
<td>2.3</td>
<td>0.0†</td>
<td>0.4†</td>
<td>0.0†</td>
</tr>
<tr>
<td>(M_{col})</td>
<td>–</td>
<td>–</td>
<td>25.4</td>
<td>–</td>
<td>3.4</td>
<td>11.7†</td>
<td>1.3</td>
<td>0.1†</td>
</tr>
<tr>
<td>(M_{vis} &gt; 700)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.2</td>
<td>2.3</td>
<td>2.8†</td>
<td>0.4†</td>
<td>0.0†</td>
</tr>
</tbody>
</table>

ATLAS Preliminary

All cross-sections here are given in fb
Plots for the lh final-state

Both the Visible and the Collinear masses are shown

- Plotted for an 800 GeV Z'
- Assuming 1 fb\(^{-1}\) of data at 14 TeV
Results for the hh final-state
Analysis for the hh final-state

Large similarities with the lh selection, but:

- Use hadronic tau trigger in combination with MET (Preliminary)
- Increase the minimum MET requirement to 40 GeV
- Different MT and pT TOT cuts than the lh channel; < 35 and < 50, respectively

Turns out to be our most powerful final-state

- Note that the primary trigger for this channel is the hadronic tau trigger
- Studies are currently underway to further explore the trigger for this channel

<table>
<thead>
<tr>
<th>Cut</th>
<th>$m = 600$ GeV</th>
<th>$m = 800$ GeV</th>
<th>$m = 1000$ GeV</th>
<th>$m = 2000$ GeV</th>
<th>$t\bar{t}$</th>
<th>W+ jets</th>
<th>Z+ jets</th>
<th>QCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>1475.3</td>
<td>567.8</td>
<td>245.9</td>
<td>12.2</td>
<td>70531.8</td>
<td>1668621.5</td>
<td>404922.8</td>
<td>1833543.8</td>
</tr>
<tr>
<td>2 Taus</td>
<td>204.0</td>
<td>102.2</td>
<td>47.8</td>
<td>3.1</td>
<td>211.3</td>
<td>250.7</td>
<td>710.0</td>
<td>831.5</td>
</tr>
<tr>
<td>Charge</td>
<td>197.1</td>
<td>98.5</td>
<td>46.1</td>
<td>2.9</td>
<td>195.3</td>
<td>183.4</td>
<td>649.9</td>
<td>829.1</td>
</tr>
<tr>
<td>MET &gt; 40</td>
<td>168.1</td>
<td>86.2</td>
<td>40.8</td>
<td>2.7</td>
<td>177.1</td>
<td>128.6</td>
<td>73.2</td>
<td>79.9†</td>
</tr>
<tr>
<td>$M_{TR} &lt; 35$</td>
<td>146.5</td>
<td>72.6</td>
<td>34.7</td>
<td>2.1</td>
<td>42.3</td>
<td>29.0†</td>
<td>49.4</td>
<td>38.8†</td>
</tr>
<tr>
<td>$P_T$ TOT &lt; 50</td>
<td>129.9</td>
<td>65.0</td>
<td>30.3</td>
<td>1.7</td>
<td>12.6</td>
<td>21.2†</td>
<td>40.3</td>
<td>27.6†</td>
</tr>
<tr>
<td>$M_{vis} &gt; 400$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.1</td>
<td>9.7†</td>
<td>13.8</td>
<td>16.8†</td>
</tr>
<tr>
<td>$M_{col}$</td>
<td>116.6</td>
<td></td>
<td></td>
<td></td>
<td>0.4†</td>
<td>0.0†</td>
<td>0.8</td>
<td>1.8†</td>
</tr>
<tr>
<td>$M_{vis} &gt; 500$</td>
<td></td>
<td>55.9</td>
<td></td>
<td></td>
<td>1.1</td>
<td>4.6†</td>
<td>10.8</td>
<td>6.1†</td>
</tr>
<tr>
<td>$M_{col}$</td>
<td></td>
<td>6.8</td>
<td></td>
<td></td>
<td>0.1†</td>
<td>0.0†</td>
<td>0.8</td>
<td>0.0†</td>
</tr>
<tr>
<td>$M_{vis} &gt; 600$</td>
<td></td>
<td></td>
<td>24.6</td>
<td></td>
<td>0.7†</td>
<td>3.0†</td>
<td>3.0</td>
<td>4.3†</td>
</tr>
<tr>
<td>$M_{col}$</td>
<td></td>
<td></td>
<td>2.5</td>
<td></td>
<td>0.02†</td>
<td>0.00†</td>
<td>0.04†</td>
<td>0.00†</td>
</tr>
<tr>
<td>$M_{vis} &gt; 800$</td>
<td></td>
<td></td>
<td></td>
<td>1.6</td>
<td>0.2†</td>
<td>0.5†</td>
<td>0.8</td>
<td>0.3†</td>
</tr>
</tbody>
</table>

All cross-sections here are given in fb
Plots for the hh final-state

Both the Visible and the Collinear masses are shown

• Plotted for an 800 GeV Z’
• Assuming 1 fb⁻¹ of data

Excellent Mass Resolution
Results for the II final-state
Analysis for the ll final-state

Large similarities with the lh selection, but:

- Obviously no hadronic tau selection
- MET requirement at 40 GeV
- MT and pT TOT cuts are < 35 and < 50, respectively
- Added a b-tag veto (displaced vertex) to help with background rejection

<table>
<thead>
<tr>
<th>Cut</th>
<th>$m = 600$ GeV</th>
<th>$m = 800$ GeV</th>
<th>$m = 1000$ GeV</th>
<th>$m = 2000$ GeV</th>
<th>Background $\sigma$ [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$t\bar{t}$</td>
<td>$W^+ \text{ jets}$</td>
<td>$Z + \text{ jets}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trigger</td>
<td>1355.9</td>
<td>516.8</td>
<td>223.7</td>
<td>11.6</td>
<td>213494.2 12365976.0 2050989.6</td>
</tr>
<tr>
<td>2 Leptons</td>
<td>132.3</td>
<td>55.2</td>
<td>25.7</td>
<td>1.1</td>
<td>13861.8 2250.3 640457.2</td>
</tr>
<tr>
<td>Charge</td>
<td>131.0</td>
<td>54.8</td>
<td>25.3</td>
<td>1.1</td>
<td>13219.4 1591.0 638777.9</td>
</tr>
<tr>
<td>MET $&gt; 40$</td>
<td>92.2</td>
<td>41.9</td>
<td>20.7</td>
<td>1.0</td>
<td>9964.5 641.9 $^\dagger$ 1205.9</td>
</tr>
<tr>
<td>$M_{TR} &lt; 35$</td>
<td>69.3</td>
<td>31.9</td>
<td>16.0</td>
<td>0.7</td>
<td>1602.6 82.5 $^\dagger$ 331.9</td>
</tr>
<tr>
<td>$P_T \text{ TOT} &lt; 70$</td>
<td>52.2</td>
<td>24.5</td>
<td>12.3</td>
<td>0.5</td>
<td>551.6 52.7 $^\dagger$ 192.7</td>
</tr>
<tr>
<td>b Veto</td>
<td>52.0</td>
<td>24.2</td>
<td>12.0</td>
<td>0.5</td>
<td>130.1 52.0 $^\dagger$ 162.0</td>
</tr>
<tr>
<td>$M_{vis} &gt; 300$</td>
<td>38.6</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>29.7 5.0 $^\dagger$ 18.4</td>
</tr>
<tr>
<td>$M_{col}$</td>
<td>2.5</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.9 1.8 $^\dagger$ 1.5</td>
</tr>
<tr>
<td>$M_{vis} &gt; 400$</td>
<td>–</td>
<td>14.9</td>
<td>–</td>
<td>–</td>
<td>8.7 1.8 $^\dagger$ 7.7</td>
</tr>
<tr>
<td>$M_{col}$</td>
<td>–</td>
<td>0.6</td>
<td>–</td>
<td>–</td>
<td>1.3 $^\dagger$ 0.9 $^\dagger$ 0.0 $^\dagger$</td>
</tr>
<tr>
<td>$M_{vis} &gt; 500$</td>
<td>–</td>
<td>–</td>
<td>6.8</td>
<td>–</td>
<td>2.6 0.9 $^\dagger$ 4.6</td>
</tr>
<tr>
<td>$M_{col}$</td>
<td>–</td>
<td>–</td>
<td>0.2</td>
<td>–</td>
<td>0.4 $^\dagger$ 0.0 $^\dagger$ 0.0 $^\dagger$</td>
</tr>
<tr>
<td>$M_{vis} &gt; 700$</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.3</td>
<td>1.7 $^\dagger$ 0.0 $^\dagger$ 4.6</td>
</tr>
</tbody>
</table>

All cross-sections here are given in fb

ATLAS
Preliminary
Results for combination
Combination of all final-states

At the level of the Visible Mass cut

- With and without inclusion of the systematics (assume 20%) estimates

ATLAS Preliminary
Combination of all final-states

At the level of the Collinear Mass cut

- With and without inclusion of the systematics (assume 20%) estimates

![Graph showing significance vs. Z' mass](image-url)

ATLAS Preliminary
What if it is not the SSM?
For Evidence or Discovery

Left: Assuming the SSM cross-section, luminosity for evidence or discovery
Right: Minimum CS needed for evidence or discovery in 1 fb$^{-1}$ of data
Conclusions

First LHC Collisions expected ~late Summer of 2009

The ATLAS and CMS Experiments are ready for collision data-taking
  • Both experiments have already taken extensive amounts of cosmics data
  • This data has already helped to gain understanding about the detectors
  • Calibration of the subsytems and refinement of the software continues

At the right mass and cross-section, a Z’ discovery could come very early
  • ~1 fb⁻¹ at 14 TeV
  • Analysis is easily extended into a massive graviton or MSSM Higgs Search

Use tau polarization to determine the spin of any observed resonance
  • Can distinguish between left and right-handed taus on a statistical basis
Backup Slides
The ATLAS Experiment
Designed to search for the Higgs and New Physics over a wide mass range

Hermetic calorimetry
- Exceptional measurement of missing transverse energy, jets to high eta

Exceptional particle identification
- Muons Efficiency ~90% Jet Rejection ~10^5
- Electrons Efficiency ~80% Jet Rejection ~10^5
- Photons Efficiency ~80% Jet Rejection ~10^3
- b-Jet ID Efficiency ~60% Light Jet Rejection ~10^2
- Tau ID Efficiency ~50% Jet Rejection ~10^2

Electron, muon and photon energy and momentum resolution of ~2-3%
ATLAS Data-taking Chain

First test of the end-to-end data-taking chain took place in September 2007

For data processing and analysis, the GRID is an absolute necessity.
Supersymmetric Higgs(es)
**Supersymmetry**

Every particle has a “super-partner” particle

**Fermions** ↔ **Bosons**

Half-Integer Spin: $\frac{1}{2}$, $\frac{3}{2}$, …  
Integer Spin: 0, 1, …

- **Quarks**
  - $u$, $c$, $t$, $\gamma$, $H$
  - $d$, $s$, $b$, $g$
  - $\nu_e$, $\nu_\mu$, $\nu_\tau$, $Z$
  - $e$, $\mu$, $\tau$, $W$

- **Leptons**
  - $\tilde{u}$, $\tilde{c}$, $\tilde{t}$, $\tilde{\gamma}$, $\tilde{H}$
  - $\tilde{d}$, $\tilde{s}$, $\tilde{b}$, $\tilde{g}$
  - $\tilde{\nu}_e$, $\tilde{\nu}_\mu$, $\tilde{\nu}_\tau$, $\tilde{Z}$
  - $\tilde{e}$, $\tilde{\mu}$, $\tilde{\tau}$, $\tilde{W}$

**Spin**

- Fermions: $\frac{1}{2}$, 1, 0
- Bosons: 0, $\frac{1}{2}$, $\frac{1}{2}$
Motivation for SUSY

Motivation for Supersymmetry

- Naturalness (Hierarchy Problem)
- Unification of the forces (gauge couplings)
- Provides a candidate for Dark Matter
MSSM Higgs at the LHC

Minimal Supersymmetric extension to the SM: (A, H, h, H±)

- As one example here, consider A / H →μμ
- Not visible in the SM
- Enhanced in the MSSM by ~tan²β; excellent mass resolution as opposed to ττ

Direct and associated production

Enhanced for large tanβ

Divide μμ analysis into two uncorrelated channels.

Initial event selection:
- Di-muon selection, low event MET, b-tag
  - 0 b-jet
  - ≥1 b-jet
    - Acoplanarity, sum pT of all jets

ATLAS Preliminary
MSSM Higgs at the LHC

Combine the 0 and $\geq 1$ b-jet analyses to increase the significance

- A very similar analysis has been explored for the $\tau\tau$ channel

$\tan\beta$ for a 5$\sigma$ Discovery
MSSM Higgses with ATLAS

The complete region of the $m_A$ – $\tan\beta$ parameter space should be accessible to ATLAS

- $m_A = 50 – 500$ GeV
- $\tan\beta = 1 - 50$
ILC Specific
Is it really the Higgs?

Properties that we will want to measure to confirm a Higgs discovery:

• What is the mass and width?
• Does it have charge?
• What are the production processes and cross-sections?
• What are the branching-ratios?
• What are the couplings?
• What is its spin?

Reasonably good precision from the LHC ~10-20% level
Get precise measurements from a high-energy e+e- collider ~1% level

The advantages of an e+e- collider:

• They’re elementary particles
• Able to collide them with well defined energy and angular momentum
• Collisions at the full center-of-mass energy
• “Democratic” particle production
• Possible to fully reconstruct the events
The International Linear Collider (ILC)

Already a huge international effort of R&D on this accelerator
  • Global design effort well underway

Parameters for the ILC (derived from the scientific goals)
  • Center-of-mass energy adjustable from 200 – 500 GeV (extendible to 1 TeV)
  • Total integrated luminosity of 500 fb\(^{-1}\) in 4 years
  • Energy stability and precision below 0.1%
  • Electron polarization of at least 80%

Cost: ~6.6 Billion USD
Location: One of three possible sites
  • Locations in the Americas, Europe and Asia: Fermilab, CERN and Japan
Timescale: Commissioning sometime beyond 2020?
Higgs Specific
The Origin of Mass

The SM says that all of the carriers of the Electromagnetic and Weak forces must have the same “symmetric” mass, of zero

- These force carriers are the \( \gamma \) and \( W^\pm/Z \), respectively
- We know from experiment that the Weak force carriers have a non-zero mass
- The symmetry is broken

Discovered by the UA1 and UA2 Experiments at CERN in 1983

The Origin of Mass

What breaks the symmetry of the Weak Interactions?

- In the theory, postulate a Higgs Field \( \phi \) and a potential energy function:
  \[
  V(\phi) = -\mu^2 |\phi|^2 + \lambda |\phi|^4
  \]
- Assume minimum is not at \( \phi = 0 \) but, some non-zero value: \( \phi_0 \)

Analogy to a ball rolling down a hill

- Direction that the ball rolled down has now been singled out from all other directions; the symmetry has been spontaneously broken

Through the Higgs Mechanism, particles obtain an “effective mass”

Peter Higgs

1964

In a recent note\(^1\) it was shown that the Goldstone theorem,\(^2\) that Lorentz-covariant field theories in which spontaneous breakdown of symmetry under an internal Lie group occurs contain zero-mass particles, fails if and only if the conserved currents associated with the internal group are coupled to gauge fields. The purpose of the present note is to report that, in a correspondence of this kind, the relation

\[
\begin{align*}
\partial_{\mu} (\Delta \psi_{\mu}) &= e \sigma_{\mu} \psi_0, \\
\partial_{\mu} (\psi_{\mu}) &= 0, \\
\end{align*}
\]

about the “vacuum” solution \( \psi_0(x) = 0, \psi_{\mu}(x) = \psi_{\mu} \)
The Higgs Field

The Higgs Field is a scalar field (think of a temperature map)

- Particles obtain an “effective mass” by interacting with the Higgs field of empty space
What we know about the Higgs

From Theory… the exact Higgs mass is unknown

- If SM is valid up to the Plank Scale \( \sim 10^{19} \) GeV, then \( M_H \) is in a limited range:

  \[
  130 \text{ GeV}/c^2 \lesssim M_H \lesssim 180 \text{ GeV}/c^2
  \]

- If there is new physics \( \sim 10^3 \) GeV:

  \[
  50 \text{ GeV}/c^2 \lesssim M_H \lesssim 800 \text{ GeV}/c^2
  \]

\( \Lambda \) is the scale of new physics beyond the Standard Model.

\( \Lambda \) is the scale of new physics beyond the Standard Model.

Vacuum stability
What we know about the Higgs

From Experiments of the past...

Higgs searches at the Large Electron-Positron Collider (LEP) at CERN

- Collider ran from 1989 through 2000
- In 2000, center-of-mass energy was 200 - 210 GeV
- Four detectors: ALEPH, DELPHI, L3 and OPAL

Present Limit from direct searches at LEP:

\[ M_H > 114.4 \text{ GeV/c}^2, \text{CL} = 95\% \]

What we know about the Higgs

From Experiments of the present…

Very aggressive searches at the CDF and D-Zero Experiments

- Proton anti-proton collider near Chicago, USA
- Running with a center-of-mass energy of 1.96 TeV
- Now looking into roughly 3 fb^{-1} of data, but no sign of the Higgs yet
- Running through 2010 is on the table; could provide a total of 8 – 10 fb^{-1}

*Note: 1 barn (b) = 10^{-28} m^2
What we know about the Higgs

ICHEP 2008 combined result from CDF and D-Zero [155, 200 GeV]

- Exclude 170 GeV/c^2 @ 95% CL
What we know about the Higgs

From other experimental measurements...

- Precision Electroweak measurements are indirectly sensitive to the Higgs mass through radiative corrections

\[ \delta_t \propto M_t^2 \]

\[ \delta_H \propto \ln \left( \frac{M_H}{M_W} \right) \]

m_W = 80.398 +/- 0.025 GeV
m_t = 172.8 +/- 1.4 GeV
What we know about the Higgs

All experimental data to date favors a light Higgs

- SM: $M_H = 87^{+36}_{-27}$ GeV; $M_H < 160$ GeV @ 95% CL
- LEP Direct Limit: $M_H > 114.4$ GeV @ 95% CL

Fit to Electroweak data performed by the LEP Electroweak Working Group (Winter 2008)
Higgs production at the LHC

**Vector Boson Fusion**

The two “spectator” quarks make for a very distinct final state.

- <10% unc. NLO

**Gluon-gluon Fusion**

Large backgrounds for low-mass Higgs searches.

- 10-20% unc. NNLO

**Associated Production**

- ~10% unc. NLO

Allows for triggering regardless of Higgs decay mode.

- <5% unc. NNLO

NLO cross-sections


M. Spira

\(\sigma(\text{pp} \rightarrow H + X) \ [\text{pb}]\)

\(\sqrt{s} = 14 \ 	ext{TeV}\)

\(M_t = 178 \ \text{GeV}\)

CTEQ6M
SM Higgs discovery final states

At low mass ($M_H < 2M_Z$)
- Dominant decay through $bb$; enormous QCD background, suppressed in $ttH$
- $H \rightarrow \tau\tau$ accessible through Vector Boson Fusion (VBF)
- $H \rightarrow WW(*)$ accessible through gluon-gluon fusion and VBF
- $H \rightarrow \gamma\gamma$ has a low BR (decays through top and $W$ loops); but due to excellent $\gamma$/jet separation and $\gamma$ resolution is still very significant
- $H \rightarrow ZZ^* \rightarrow 4l$ also accessible

For higher masses
- $H \rightarrow WW$ and $H \rightarrow ZZ \rightarrow 4l$ final-states

Includes quark mass uncertainties ($t$, $b$, $c$) and $\alpha_s(M_Z)$. 

A. Djouadi hep-ph/0503172
Forward Jet Tagging and the Central Jet Veto

We can get the upper-hand in the VBF channels

Forward Jet Tagging
- D. Rainwater, D. Zeppenfeld, et al.

\[ \eta_{j1} \cdot \eta_{j2} < 0 \]
\[ |\Delta \eta_{jj}| > 3.5 - 4 \]
\[ m_{jj} > 500 - 700 \text{ GeV} \]

Central Jet Veto
- V.Barger, K.Cheung and T.Han in PRD 42 3052 (1990)

Veto events with extra jets in the central region

Tagging Jets
VBF $H \rightarrow \tau\tau$

A very significant channel for low masses
- Important for studying the coupling of Higgs to leptons
- Three final states lepton-lepton, lepton-hadron, hadron-hadron
- Triggers for the fully hadronic mode are under investigation

Mass reconstruction via the collinear approximation
- Approximation breaks down when the two taus are back-to-back
- Mass resolution limited by missing transverse energy ($\sim 8 – 10$ GeV)

Experimental issues:
- Tau tagging (Likelihood, Neural Net methods)
- $Z$+jets background (especially for low masses)
- $tt$ rejection (b-jet ID and veto for lepton-lepton)
VBF $H \rightarrow \tau \tau$

Data-driven control samples are being explored for many backgrounds

- The relative contributions from different jet multiplicities are not known
- Unknowns related to critical analysis cut-specific variables exist

For the dominant background, collect $Z \rightarrow \mu \mu$ and $Z \rightarrow ee$ events from data and use TAUOLA to decay the leptons to taus

In this way we can emulate each of the lepton-lepton, lepton-hadron and hadron-hadron final states

Obtain both the background shape and normalization from data
SM Higgs Discovery Potential

Luminosity for SM Higgs discovery or exclusion

- ~few 100 pb⁻¹, some exclusion @ 95% CL
- ~1 fb⁻¹, 5σ discovery if M_H ~160 - 170 GeV
- ~10 fb⁻¹, discovery over a broad mass range
Tau Specific
Hadronic Tau Selection

Zofia has already given a number of talks on high-pT tau selection:
http://indico.cern.ch/getFile.py/access?contribId=1&resId=1&materialId=slides&confId=18959
http://indico.cern.ch/getFile.py/access?contribId=3&resId=0&materialId=slides&confId=17392

Her studies have sculpted the hadronic tau selection criteria for Z’
  - e.g., cut on the tau likelihood as a function of the tau ET (see next few slides)

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>35-70</th>
<th>70-140</th>
<th>140-280</th>
<th>280-560</th>
<th>560-1120</th>
<th>1120-2240</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_T &gt; 60$ GeV + $N_{\text{trk}} 1.3$</td>
<td>8.06±0.05</td>
<td>80.18±0.07</td>
<td>99.30±0.01</td>
<td>99.97±0.00</td>
<td>100.00±0.00</td>
<td>100.00±0.00</td>
</tr>
<tr>
<td>$</td>
<td>\text{charge}</td>
<td>= 1$ + $llh$ cut</td>
<td>1.48±0.02</td>
<td>13.09±0.06</td>
<td>10.84±0.05</td>
<td>8.13±0.04</td>
</tr>
<tr>
<td>N Events for 1 fb$^{-1}$</td>
<td>$4\cdot10^7$</td>
<td>$4\cdot10^6$</td>
<td>$1\cdot10^6$</td>
<td>$9\cdot10^5$</td>
<td>$3\cdot10^3$</td>
<td>40</td>
</tr>
</tbody>
</table>
Tau ID in ATLAS

- **two algorithms**: calorimetry-based (*tauRec*) and track-based (*tau1p3p*)
- **Calorimetry**: collimated energy deposition, $\pi^0$'s produced, isolation region, EM radius, EM fraction
- **Tracking**: low track multiplicity, isolation region, positive impact parameter, invariant mass and width of track system (3-prong)

- **Highlights from Data Preparation Perspective**:
  - $\tau$-specific calibrations need to be understood
  - tracking objects associated with calo objects: good sensitivity to detector performance
**Tau ID in ATLAS**

**Track based approach**

- Identify "good quality" hadronic track, $p_T > 9$ GeV,
- Find nearby "good quality" tracks with $p_T > 2$ GeV in $\Delta R < 0.2$

**$\tau_{1P}$**
- No nearby-track $(\phi, \eta)$ from track at vertex
- Build $E_T^{\text{flow}}$, use $\Delta R < 0.2$
- Build discrimination variables
  - Use $\Delta R < 0.2$ as a "core",
  - $0.2 < \Delta R < 0.4$ for isolation only
- $\tau_{1P}$ - single-prong candidates

**$\tau_{3P}$**
- 2 nearby tracks
  - $(\phi, \eta)$ from barycentre of tracks
  - $\Sigma$ charge = $\pm 1$
- Build $E_T^{\text{flow}}$, use $\Delta R < 0.2$
- Build discrimination variables
  - Use $\Delta R < 0.2$ as a "core",
  - $0.2 < \Delta R < 0.4$ for isolation only
- $\tau_{3P}$ - three-prong candidates
Tau Efficiency

<table>
<thead>
<tr>
<th>faking tau</th>
<th>estimated FF</th>
</tr>
</thead>
<tbody>
<tr>
<td>electrons</td>
<td>~2%</td>
</tr>
<tr>
<td>muons</td>
<td>~0.5%</td>
</tr>
<tr>
<td>jets</td>
<td>~0.1%</td>
</tr>
</tbody>
</table>

FR depends on event activity
and tau ID requirements, so this
table just gives a rough order of
magnitude estimate

Efficiency of reconstruction and rec/id with \(\text{tauRec}\) as a function of (a) \(P_T\) and (b) \(\eta\) in Z sample.
Tau Identification and QCD rejection (2)

To identify taus:

• Overlap removal: remove muons and tight electrons if within $R=0.2$
• Require $N_{\text{trk}} = 1,3$ and charge = 1
• Cut on $llh$ variable as a function of $E_T$:
  $llh > 6$ ($E_T < 100$); $llh > 4$ ($100 < E_T < 150$); $llh > 2$ ($150 < E_T < 250$); $llh > 0$ ($E_T > 250$)
• Tau $p_T > 60$ GeV

<table>
<thead>
<tr>
<th>Cut</th>
<th>Efficiency %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_T &gt; 60$ GeV</td>
<td>89.1 %</td>
</tr>
<tr>
<td>$N_{\text{trk}} +</td>
<td>\text{charge}</td>
</tr>
<tr>
<td>$llh$ cut</td>
<td>46.6 %</td>
</tr>
</tbody>
</table>
**Tau energy resolution**

*Resolution extracted from gaussian fit in 2 sigma to $E_{\text{calib}}/E_{\text{vis, true}}$*

**H1 style calibrated taus:**
- Resolution: 6.78 %
- Relative resolution (mean/sigma) = 6.56%

**Overall calibrated taus:**
- Resolution: 6.36 %
- Relative resolution (mean/sigma) = 6.78%
Trigger for ll and lh channels

- **Electron trigger**: e25i || e60
  - Used for eh, ee, and eμ final states
  - At high P_T e25i non optimal due to isolation
  - use combination of e25i || e60
- **Muon trigger**: mu20
  - Used for μh, μμ, μe final states

- Trigger studies performed using trigger decision after EF, efficiency shown wrt to highest Pt lepton

Non optimal, looking forward to samples with
Release 13 to study tau+e and tau+μ menu items

| Trigger menu | e25i | e60 | e25i || e60 | μ/μ |
|--------------|------|-----|--------|-------|-----|
| Efficiency wrt to truth | 70.5% | 73.4% | 77.1% | μ/μ |
| Efficiency wrt offline | 85.8% | 92.1% | 93.4% | μ/μ |
| Efficiency wrt to truth | 83.5% | 78.9% | 87.3% | μ/μ |
| Efficiency wrt offline | 91.3% | 94.2% | 95.5% | μ/μ |
| Efficiency wrt to truth | 67.4% | 70.1% | 73.0% | μ/μ |
| Efficiency wrt offline | 84.5% | 91.2% | 92.4% | μ/μ |
**Trigger for hh channel**

- Use tau35i+XE40 to trigger events with hh final state.
- Total rate of such item is 4Hz, predicted unprescaled at $10^{32}$ lumi.

See Marc-Andre Dufour’s talk on Trigger Open meeting (Menus), the 17 of Jan

http://indico.cern.ch/getFile.py/access?contribId=1&resId=0&materialId=slides&confId=24859

- Trigger studies performed using trigger decision after EF, efficiency shown wrt to highest Pt hadronic tau.

<table>
<thead>
<tr>
<th>Trigger menu</th>
<th>tau35i</th>
<th>tau35i + XE40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency wrt to truth</td>
<td>63.6%</td>
<td>41.4%</td>
</tr>
<tr>
<td>Efficiency wrt offline</td>
<td>77.0%</td>
<td>51.1%</td>
</tr>
</tbody>
</table>
We can distinguish between left- and right-handed taus on a statistical basis.

Plots of the fractional energy distributions are taken from:

Z’ Specific
Systematics

“Official” CSC systematic sources were considered:

<table>
<thead>
<tr>
<th>Source</th>
<th>Relative uncertainty</th>
<th>600 GeV</th>
<th>800 GeV</th>
<th>1000 GeV</th>
<th>2000 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Energy Scale</td>
<td>±0.5%</td>
<td>0.4</td>
<td>0.4</td>
<td>0.3</td>
<td>0.1 %</td>
</tr>
<tr>
<td>Electron Energy Resolution</td>
<td>σ(ET) ⊕ 0.012ET</td>
<td>0.3</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2 %</td>
</tr>
<tr>
<td>Electron ID Efficiency</td>
<td>±1%</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.3 %</td>
</tr>
<tr>
<td>Muon Energy Scale</td>
<td>±1%</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1 %</td>
</tr>
<tr>
<td>Muon Energy Resolution</td>
<td>σ(pT) ⊕ 0.011pT ⊕ 1.710⁻⁴pT²</td>
<td>0.4</td>
<td>0.2</td>
<td>0.1</td>
<td>0.0 %</td>
</tr>
<tr>
<td>Muon ID Efficiency</td>
<td>±5%</td>
<td>1.8</td>
<td>1.8</td>
<td>1.8</td>
<td>1.6 %</td>
</tr>
<tr>
<td>Tau Energy Scale</td>
<td>±5%</td>
<td>10.1</td>
<td>6.0</td>
<td>5.0</td>
<td>3.0 %</td>
</tr>
<tr>
<td>Tau Energy Resolution</td>
<td>σ(E) ⊕ 0.45√E</td>
<td>0.8</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1 %</td>
</tr>
<tr>
<td>Tau ID Efficiency</td>
<td>±5%</td>
<td>6.4</td>
<td>6.5</td>
<td>6.5</td>
<td>7.0 %</td>
</tr>
<tr>
<td>Jet Energy Scale</td>
<td>±7%</td>
<td>1.2</td>
<td>1.0</td>
<td>1.1</td>
<td>1.2 %</td>
</tr>
<tr>
<td>Jet Energy Resolution</td>
<td>σ(E) ⊕ 0.45√E</td>
<td>0.3</td>
<td>0.4</td>
<td>0.5</td>
<td>0.3 %</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>12.2</td>
<td>9.1</td>
<td>8.5</td>
<td>7.8 %</td>
</tr>
</tbody>
</table>

A conservative sum in quadrature gives a total of ~20%

Large systematics for backgrounds due to poor MC statistics

- Assume systematics on background will be the same as the signal (~20%)
Mass Reconstruction

Full di-tau mass reconstruction is possible

- Use the collinear approximation when the parent particle is heavily boosted
- Approximation breaks down when the decay daughters are back-to-back
  - A heavy $Z'$ is more or less generated at rest in the lab-frame
  - Two taus are most often quite nearly back-to-back
  - Could consider cutting on high $p_T$, but high $m_\tau$ helps to reject background
- A large statistics sample will be important for any asymmetry measurement

\[ m_{\tau\tau}^2 = (p_{\tau 1} + p_{\tau 2})^2 = \frac{2 p_1 \cdot p_2}{x_1 x_2} + 2 m_\tau^2 \]

\[ p_{T,\tau 1} + p_{T,\tau 2} = \frac{p_{T,\tau 1}}{x_1} + \frac{p_{T,\tau 2}}{x_2} \]

\[ = p_{T,\tau 1} + p_{T,\tau 2} + p_{T,\text{miss}} \]

Monte Carlo

Truth

Entries 4701
Mean    2.94
RMS     0.35
Underflow 0.00
Overflow  0.00
Another cut that we use is the total pT of the event

- Use the hadronic tau, lepton, MET and leading-jet
The CMS Experiment
Expected Event Rates

ATLAS with LHC at $\mathcal{L} = 10^{33}$ cm$^{-2}$ s$^{-1}$

<table>
<thead>
<tr>
<th>Process</th>
<th>Events / s</th>
<th>Events in 10 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W\rightarrow e\nu$</td>
<td>15</td>
<td>$10^8$</td>
</tr>
<tr>
<td>$Z\rightarrow ee$</td>
<td>1.5</td>
<td>$10^7$</td>
</tr>
<tr>
<td>$t\bar{t}bar$</td>
<td>1</td>
<td>$10^6$</td>
</tr>
<tr>
<td>$b\bar{b}bar$</td>
<td>$10^6$</td>
<td>$10^{12-10^{13}}$</td>
</tr>
<tr>
<td>$H (m=130)$</td>
<td>0.02</td>
<td>$10^5$</td>
</tr>
</tbody>
</table>

Many of these processes become backgrounds to New Physics searches... ...more on this later
An Unexpected Event?
The media likes to get carried away… Will a Black Hole swallow the Earth?
I think we’re safe…

~4.5 Billion Years

Earth-based Accelerators
MSSM Higgs at the LHC

Summary of CMS reach in $M_A \tan \beta$
CMSSM

Constrained MSSM

- O. Buchmueller et al., arXiv:0707.3447v2 [hep-ph]
- CMSSM: $M_h = 110 (+8)(-10) \pm 3$ (theo.) GeV
- Includes CDM, flavor physics and $a_\mu$ experimental data

<table>
<thead>
<tr>
<th>CMSSM parameter</th>
<th>Preferred value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_0$</td>
<td>$(85^{+19}_{-25})$ GeV/c$^2$</td>
</tr>
<tr>
<td>$M_{1/2}$</td>
<td>$(280^{+140}_{-140})$ GeV/c$^2$</td>
</tr>
<tr>
<td>$A_0$</td>
<td>$(-360^{+300}_{-140})$ GeV/c$^2$</td>
</tr>
<tr>
<td>$\tan\beta$</td>
<td>$10^{+9}_{-4}$</td>
</tr>
<tr>
<td>$\text{sgn}(\mu)$</td>
<td>$+1$ (fixed)</td>
</tr>
</tbody>
</table>

Table 2

Values of the CMSSM parameters at the globally preferred $\chi^2$ minimum, and corresponding 1-sigma errors. The lower limit of Eq. 2 is included.

chi$^2$ / ndf = 17.34 / 14

Figure 2. Mass spectrum of super-symmetric particles at the globally preferred $\chi^2$ minimum. Particles with mass difference smaller than 5 GeV/c$^2$ have been grouped together.
Impact Parameter

Displaced vertices present in Zbb and $t\bar{t}$

**Impact Parameter Significance** $\equiv d_0/\sigma_{d_0}$

- Transverse impact parameter resolution
  - $\sim 15 \, \mu m$ for $P_T = 20$ GeV
- Transverse primary vertex spread
  - $\sim 15 \, \mu m$, taken into account

**Isolation + Impact Parameter Criteria**

- $O(10^2)$ Rejection for Zbb
- $O(10^3)$ Rejection for $t\bar{t}$
  - for signal efficiency $O(80\%)$

Effect of pile-up on signal significance $\leq 5\%$
Higgs Properties
Azimuthal angle $\phi$ between decay planes in the rest frame of Higgs
$$F(\phi) = 1 + \alpha \cos(\phi) + \beta \cos(2\phi)$$

Polar angle $\theta$ between lepton and the Z momentum in Z rest frame
$$G(\theta) = L \sin^2(\theta) + T(1+\cos^2(\theta)), \ R=(L-T)/(L+T)$$

$M_{Z*}$ distribution for $M_H < 2 M_Z$,
$$d\Gamma_H/dM_{Z*}^2 \sim \beta^n \text{ near threshold (n=1 in SM)}$$
$$\beta^2=\frac{[1-(M_Z+M_{Z*})^2/M_H^2][1-(M_Z-M_{Z*})^2/M_H^2]}{[1-(M_Z+M_{Z*})^2/M_H^2][1-(M_Z-M_{Z*})^2/M_H^2]}$$

Recent ATLAS fast simulation study on sensitivity to $F(\phi)$ and $G(\theta)$
for exclusion of $0^-, 1^+, 1^-$ for $M_H > 2M_Z$: SN-ATLAS-2003-025