Part 4: Search for the Higgs Boson

4th July 2012  A great day for science / particle physics
Some convincing signals

\[ H \rightarrow \gamma\gamma \]

\[ H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^- \ell^+\ell^- \]
H → WW → ℓν ℓν

Updated ATLAS analysis (since 4th July) including the 2012 data new
Compatibility with background only hypothesis

Observation of a new resonance in the search for the Higgs boson
Evolution of the excess with time

ATLAS Preliminary

Energy-scale systematics not included
Next important steps:
- Updated ATLAS analyses on tt and bb channels awaited
- Determination of parameters of the resonance (mass, spin / CP, couplings)
- Most of this will be summarized in the dedicated lecture by Meenakshi Narain

- I will concentrate on a few important SUSY results in the following
5.1 Search for Supersymmetry

- $qq$, $qg$ or $gg$ in the initial state $\rightarrow$ production of coloured SUSY particles is dominant, via strong interaction

- Drell-Yan production of sleptons, charginos and neutralinos (lower cross sections)
Cross sections for SUSY production processes

NLO corrections in QCD perturbation theory are known.
Decays of heavy SUSY particles $\rightarrow$ long and complex decay chains

Invariants in R-parity conserving SUSY: jets, $E_T^{\text{miss}}$ (2 LSPs)
An example of a search for $E_T^{\text{miss}} + \text{jets}$ \hspace{1em} (1.04 fb$^{-1}$)

Selection of events with $E_T^{\text{miss}} + \text{jets}$

Split the analysis according to jet multiplicities: 2, 3 and 4 jets

(different sensitivity for different squark/gluino mass combinations, i.e. in different regions of SUSY parameter space)

Definition of signal regions:

\[
m_{\tilde{g}} = m_{\tilde{q}}
\]
Three different analyses, depending on squark / gluinos mass relations:

(i) dijet analysis
small $m_0$, $m(\text{squark}) < m(\text{gluino})$

(ii) 3-jet analysis
intermediate $m_0$, $m(\text{squark}) \approx m(\text{gluino})$

(iii) Gluino analysis
large $m_0$, $m(\text{squark}) > m(\text{gluino})$
An example of a search for $E_T^{\text{miss}} + \text{jets}$ (1.04 fb$^{-1}$)

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Definition of signal regions:
### Summary on control of backgrounds using data

(control regions, very important!!)

**A:** \(Z + \text{jet events, } Z \rightarrow \text{ee} \)

(to estimate \(Z \rightarrow \nu\nu \) background, likewise \(\gamma + \text{jet events were used} \))

**B:** QCD multijet background

(reverse cut on \(\Delta \phi \) (jet, \(E_T^{\text{miss}} \))

**C:** \(W \rightarrow l\nu + \text{jet control region} \)

(select events with one lepton, \(30 < M_T(l,E_T^{\text{miss}}) < 100 \text{ GeV} \),

no b-jet to suppress top contribution)

**D:** top quark control region

(same selection as for \(W \) events, but require b-tag)
Observed and expected event numbers (from Standard Model processes)

dominant backgrounds:
- W/Z + jets
- \(t\bar{t}\) production

Normalized in control regions!
(as explained on the previous slide)
Interpretation of the results in the \((m_{\text{gluino}}, m_{\text{squark}})\)-plane as 95\% C.L. exclusion limits in a simplified SUSY model:

- \(m_X = 0\)

- masses of gluinos and of 1\textsuperscript{st} and 2\textsuperscript{nd} generation squarks as given on plot

- all other SUSY masses are assumed to be decoupled, with masses of 5 TeV

Large area of mass combinations excluded;
Limits do not apply to stop / sbottom production
mSUGRA interpretation

\[ \tan \beta = 10, \quad A_0 = 0, \quad \mu > 0 \]
mSUGRA interpretation, including 2012 data

MSSM/cMSSM interpretation (for equal squark and gluino masses):

\[ L = 5.8 \text{ fb}^{-1} \text{ at } \sqrt{s} = 8 \text{ TeV} \quad m(\text{squark}), m(\text{gluino}) > 1500 \text{ GeV} \]
Looking for “natural” SUSY

• Search for stops and sbottoms in gluino decays
  - if other squarks are very heavy, gluino will decay into sbottoms and stops with high branching ratio

• Search for stop and sbottom pair production
  - to close the loophole that the “gluino is too heavy”
ATLAS: $\tilde{g} \to \tilde{t}, \tilde{b}$

4-6 jets (≥3 b-jets), no leptons.

Allowed decays depend on masses

Upper plots – 2-body cascade decays

Lower plots – 3-body decays
Direct Stop searches

Heavy stop $> m_t$: look for hadronic or leptonic top decays with extra $E_T^{miss}$

$$\tilde{t}_1 \rightarrow t \tilde{\chi}_d^0 \rightarrow Wb \tilde{\chi}_d^0$$

Light stop $< m_t$: look for top-like decay via chargino. Signal events contain lower $p_T$ leptons, and subsystem mass below $2m_t$

$$m_t > m_\tilde{t} > m_{\tilde{\chi}_1^\pm}$$

$$\tilde{t} \rightarrow b \tilde{\chi}_d^+ \rightarrow b W^{(*)} \tilde{\chi}_d^0$$

**ATLAS Preliminary**

Data 2011 ($\sqrt{s} = 7$ TeV)

- Standard Model
- $t\bar{t}$
- Single top, dibosons, W+jets
- $Z\gamma^*$+jets

$$(m(t), m_\tilde{t}) = (112,55) \text{ GeV}$$

Signal at low $p_T$
Combined stop exclusion

\[ \tilde{t}_1 \rightarrow b + \tilde{\chi}_1^\pm, \tilde{\chi}_1^- \rightarrow W^{+} + \tilde{\chi}_1^0 \text{ (BR=1, } m_{\tilde{t}} < 200 \text{ GeV)}; \quad \tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0 \text{ (BR=1, } m_{\tilde{t}} > 200 \text{ GeV)} \]

\[ \int L \, dt = 4.7 \text{ fb}^{-1} \quad \sqrt{s} = 7 \text{ TeV} \]

ATLAS Preliminary

Expected limits (nominal)

\[ m_{\tilde{t}_1} \text{ production: } \tilde{t}_1 \rightarrow b + \tilde{\chi}_1^\pm, \tilde{\chi}_1^- \rightarrow W^{+} + \tilde{\chi}_1^0 (\text{BR=1, } m_{\tilde{t}} < 200 \text{ GeV}); \quad \tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0 (\text{BR=1, } m_{\tilde{t}} > 200 \text{ GeV}) \]

All limits at 95\% CL_{sus}
Is SUSY dead?

A. Parker, ICHEP 2012, SUSY summary talk

- Under attack from all sides, but not dead yet.
- The searches leave little room for SUSY inside the reach of the existing data.
- But interpretations within SUSY models rely on many simplifying assumptions, and so care must be taken when making use of the limit plots.
- Plausible “natural” scenarios still not ruled out: stop and/or RPV scenarios have few constraints.
- There is no reason to give up hope of finding SUSY at the LHC.
Summary of results on searches for Physics Beyond the Standard Model in ATLAS in ATLAS

**ATLAS Exotics Searches* - 95% CL Lower Limits (Status: ICHEP 2012)**

<table>
<thead>
<tr>
<th>Type</th>
<th>Process</th>
<th>Mass Limit [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large ED (ADD)</td>
<td>monojet + (E_{T,miss})</td>
<td>3.8</td>
</tr>
<tr>
<td>Large ED (ADD)</td>
<td>monophoton + (E_{T,miss})</td>
<td>1.7</td>
</tr>
<tr>
<td>Large ED (ADD)</td>
<td>dihphoton, (m_{\phi})</td>
<td>1.29</td>
</tr>
<tr>
<td>UED</td>
<td>dihphoton + (E_{T,miss})</td>
<td>1.41</td>
</tr>
<tr>
<td>RS1 with (k/M_{pl}=0.1)</td>
<td>dihphoton, (m_{\phi})</td>
<td>2.06</td>
</tr>
<tr>
<td>RS1 with (k/M_{pl}=0.1)</td>
<td>ZZ resonance, (m_{ll}/m_{ll})</td>
<td>2.16</td>
</tr>
<tr>
<td>RS1 with (k/M_{pl}=0.1)</td>
<td>WW resonance, (m_{\ell\ell}/m_{\ell\ell})</td>
<td>1.22</td>
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<tr>
<td>(g_{\gamma}/m_{\phi}=0.20)</td>
<td>(tt\rightarrow) jets, (m_{X})</td>
<td>0.63</td>
</tr>
<tr>
<td>RS with (BR(g_{\gamma}\rightarrow\gamma j)\ 0.925)</td>
<td>(\gamma\rightarrow j+)jets, (m_{\gamma})</td>
<td>1.50</td>
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<tr>
<td>ADD BH ((M_{N}/M_{pl}=3))</td>
<td>SS dimuon, (N_{part})</td>
<td>1.75</td>
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<tr>
<td>ADD BH ((M_{N}/M_{pl}=3))</td>
<td>leptons +(Z, Z')</td>
<td>2.21</td>
</tr>
<tr>
<td>Quantum black hole</td>
<td>dijet, (F_{\text{ch. part.}})</td>
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<tr>
<td>Color octet scalar</td>
<td>dijet resonance, (m_{\phi})</td>
<td>0.55</td>
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<td>Major. neutr. (LRSM, no mixing)</td>
<td>(2) lept. +jets, (m_{\ell\ell})</td>
<td>0.55</td>
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<tr>
<td>Vector-like quark</td>
<td>(CC)</td>
<td>1.0</td>
</tr>
<tr>
<td>Vector-like quark</td>
<td>(NC)</td>
<td>1.0</td>
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<tr>
<td>Techni-hadrons</td>
<td>(WZ) resonance, (k/\theta_{u})</td>
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<tr>
<td>4th generation</td>
<td>(Q_{4})</td>
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<td>Excited fermions</td>
<td>(\gamma\rightarrow\gamma) resonance, (m_{\gamma})</td>
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<tr>
<td>Exotic scalars</td>
<td>dijet resonance, (m_{\phi})</td>
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<tr>
<td>Other</td>
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<td></td>
</tr>
</tbody>
</table>
Summary of the lectures

• After a long way of design, construction, installation, commissioning of both machine and experiments the LHC had an excellent start in 2010

• The performance of the accelerator and the experiments is superb; (In 2012: an integrated luminosity > 12 fb$^{-1}$ already)

• The Standard Model has been established, all relevant processes measured; In many areas measurements have reached the precision phase

• A new boson has been discovered with a mass around 125/126 GeV; Exiting analyses ahead of us to understand the nature of this new particle

• So far: no deviations from the Standard Model seen, but the LHC potential has by far not yet been fully exploited!
End of lectures
\[ \mathcal{L}_{\text{TGC}} = i e g_1^\gamma (A_\mu (\partial_\mu W^-_\nu (\partial_\nu W^-_\mu) W^+_{\nu \mu} - A_\mu (\partial^\mu W^{+\nu} - \partial^\nu W^{+\mu}) W^-_{\nu \mu}) \\
+ i e \kappa_\gamma (\partial_\mu A_\nu - \partial_\nu A_\mu) W^{+\mu} W^{-\nu} \\
+ i e \cot \theta_W g_1^Z Z_\mu (\partial_\mu W^-_\nu - \partial_\nu W^-_\mu) W^+_{\nu \mu} - Z_\mu (\partial^\mu W^{+\nu} - \partial^\nu W^{+\mu}) W^-_{\nu \mu}) \\
+ i e \cot \theta_W \kappa_Z (\partial_\mu Z_\nu - \partial_\nu Z_\mu) W^{+\mu} W^{-\nu} \\
+ i e \frac{\lambda_\gamma}{M_W^2} ((\partial_\mu A_\rho - \partial_\rho A_\mu) (\partial^\rho W^{+\nu} - \partial^\nu W^{+\rho}) (\partial_\nu W^{-\mu} - \partial_\mu W^{-\nu})) \\
+ i e \cot \theta_W \frac{\lambda_Z}{M_W^2} ((\partial_\mu Z_\rho - \partial_\rho Z_\mu) (\partial^\rho W^{+\nu} - \partial^\nu W^{+\rho}) (\partial_\nu W^{-\mu} - \partial_\mu W^{-\nu})) \]