Supersymmetry Searches in ATLAS
1.1.4 Shortcomings of the Standard Model

The SM has been introduced as a physics success in describing and predicting observations in nature with satisfactory and sometimes astounding accuracy. Unfortunately, the SM does not provide a complete picture. There is no obvious candidate particle to explain the nature of dark matter, which will be discussed in the coming section, and the SM fails to confront the matter–antimatter asymmetry in the universe.

Gravity is not incorporated into the SM, with the strength of the gravitational force being many orders of magnitude lower than the strength of the other forces. In fact, the gravitational force does not reach a strength comparable to that of the other forces until energies approaching $10^{18}$ GeV with possible unification of the four forces occurring around the Planck scale $\times_{\text{PL}}$. The reason for this hierarchy of scales in physics is a mystery and it leads to the hierarchy problem explained below.

The Higgs boson mass, both by necessity and according to recent observations, is at the EW scale of $125 \text{ GeV}$ according to recent experimental results. This mass is subject to radiative corrections from quantum loop interactions with fermions and bosons. An example of such a loop is shown in Figure 1. These quantum corrections are of order $m^2_H f^2 \times_{\text{scale}}$ where $f$ is a factor containing other terms, including the mass of the particle the Higgs is coupling to and the associated coupling squared, and $\times_{\text{scale}}$ is the cutoff scale of the theory. That is to say, the Higgs mass term is sensitive to the scale of physics beyond the EW scale.

For a cutoff $\times_{\text{scale}}$ scale of $1 \text{ TeV}$, the corrections to the Higgs mass are small, with large divergences being avoided. If the SM as it is now were the final word and therefore considered valid up to $\times_{\text{PL}}$, the Higgs mass will be subject to enormous corrections. The quantum corrections to the physical Higgs mass term require the bare Higgs mass to be $O(\times_{\text{PL}}^2)$ before the loop corrections. The model then needs to be fine-tuned such that quadratic terms of this order cancel to within $10^{-12}$ GeV. Such exact tuning without adequate physical motivation spoils the naturalness of the theory, making it far less attractive. This problem serves as motivation for theories suggesting the existence of new physics between the EW and Planck scales, with the SM being a low energy approximation valid up to $\times_{\text{TeV}}$. The Higgs boson discovery in 2012 → the SM is complete!

... but open questions remain.
Chapter 1. Theory and Motivation

1.1.4 Shortcomings of the Standard Model

The SM has been introduced as a physics success describing and predicting observations in nature with satisfactory and sometimes astounding accuracy. Unfortunately, the SM does not provide a complete picture. There is no obvious candidate particle to explain the nature of dark matter, which will be discussed in the coming sections, and the SM fails to confront the matter–antimatter asymmetry in the universe. Gravity is not incorporated into the SM, with the strength of the gravitational force being many orders of magnitude lower than the strength of the other forces. In fact, the gravitational force does not reach a strength comparable to that of the other forces until energies approaching $10^{18}$ GeV, with possible unification of the four forces occurring around the Planck scale $\mathcal{P}L$. The reason for this hierarchy of scales in physics is a mystery and it leads to the hierarchy problem, explained below.

Figure: Feynman diagram depicting a fermion loop contributing a correction to the Higgs mass. The Higgs boson mass, both by necessity and according to recent observations, is at the EW scale of $\mathcal{O}(100)$ GeV. This mass is subject to radiative corrections from quantum loop interactions with fermions and bosons. An example of such a loop is shown in Figure: These quantum corrections are of order $m^2_H/\mathcal{P}L^2$ where $f$ is a factor containing other terms including the mass of the particle the Higgs is coupling to and the associated coupling squared $k$, and $\mathcal{P}L$ is the cutoff scale of the theory. That is to say, the Higgs mass term is sensitive to the scale of physics beyond the EW scale. For a cutoff $\mathcal{P}L$ scale of $10^{18}$ TeV the corrections to the Higgs mass are small, with large divergences being avoided. If the SM as it is now were the final word and therefore considered valid up to $\mathcal{P}L$, the Higgs mass will be subject to enormous corrections $\mathcal{P}L^2$. The quantum corrections to the physical Higgs mass term would require the bare Higgs mass to be $\mathcal{O}(\mathcal{P}L)$ before the loop corrections. The model then needs to be fine-tuned such that quadratic terms of this order cancel to within $\mathcal{O}(10^2)$ GeV. Such exact tuning without adequate physical motivation spoils the naturalness of the theory, making it far less attractive. This problem serves as motivation for theories suggesting the existence of new physics between the EW and Planck scales, with the SM being a low energy approximation valid up to $\mathcal{P}L$. The Standard Model

plus Supersymmetry?

\begin{align*}
Q|\text{fermion}\rangle &= |\text{boson}\rangle \\
Q|\text{boson}\rangle &= |\text{fermion}\rangle
\end{align*}
SUSY searches at ATLAS

Production modes

Strong production

Electroweak production

Third generation production

Gluinos/light squarks

Final state signatures

R-parity conservation

MET, Dark matter?

Stable LSP

R-parity violation

Multiple final state particles

LSP → SM particles

Long lived particles

Displaced decays

Sparticle lifetimes

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
Electroweak SUSY

- Talk by Huan Ren on Wednesday

Lower production cross-section but:

- less hadronic activity
  -> trigger on leptons

- light charginos/neutralinos
  -> naturalness

- light sleptons
  -> neutralino co-annihilation
  -> DM

Experimental challenges

Many production modes and final states explored in run 1

[ATLAS Preliminary]

- Expected limits
- Observed limits

All limits at 95% CL

20.3 fb⁻¹, √s=8 TeV

Status: Feb 2015
Recent ATLAS summary paper on run 1 searches for third generation squarks [arXiv:1506.08616]
Strongly produced SUSY

Talk by I. Deigaard on Wednesday

Strong/ EW production

(b-)jets

leptons

Gravitino LSP
(<1 GeV)

γ Photons

Bino NLSP

Bino/higgsino NLSP

Wino NLSP

Di-photon, photon+jets, photon+b-jet, photon+lepton

(μ>0) (μ<0)

Experimental tools

✓ Photon triggers
✓ 10 SRs in total
✓ HT & MET → high NLSP masses
✓ $\Delta \phi_{\text{min}}(\gamma, E_{T}^{\text{miss}}), \Delta \phi_{\text{min}}(\text{jet}, E_{T}^{\text{miss}})$ to reject fake MET background

Main backgrounds

W+gamma
W→lnu
W→lνu
Data control regions
tt+gamma
jet→gamma
e→gamma
Data driven matrix method

Search for photonic signatures
gauge mediated SUSY (GGM)

NLSP is prompt → Non-prompt
bino-NLSP: arXiv:1409.5542

arXiv:1507.05493
Strongly produced SUSY

No evidence for physics beyond SM:

- M(gluino) lower limit @ ~1140 GeV for higgsino-bino NLSP (right)
- M(gluino) lower limit @ ~1260 GeV for higgsino-bino NLSP (lower left)
- M(gluino) lower limit @ ~1300 GeV for bino NLSP (lower right)

\[ m_{\tilde{g}} \geq 1140 \text{ GeV} \] for higgsino-bino NLSP (right)
\[ m_{\tilde{g}} \geq 1260 \text{ GeV} \] for higgsino-bino NLSP (lower left)
\[ m_{\tilde{g}} \geq 1300 \text{ GeV} \] for bino NLSP (lower right)
Strongly produced SUSY

Search for SUSY in events with two same-flavour opposite-sign leptons

Experimental tools
- Lepton triggers
- 1 SR (on-Z), 5 SR (off-Z)
- HT & MET → high NLSP masses
- \( \Delta \phi_{\text{min}}(\text{jet}, E_T^{\text{miss}}) \) to reject fake MET background

Main backgrounds
- \( \text{tt} \)
- \( \text{WW} \)
- Z+jets

Data-driven jet smearing

\( \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \)

\( \Delta \phi (\text{jet}, E_T^{\text{miss}}) > 0.4 \)

Data events
Strongly produced SUSY

Observation in agreement with SM for off-Z analysis SRs

CMS reported an excess in this channel \[\text{[arXiv:1502.06031]}\]

Excess of events observed in on-Z SR

- 1.7 $\sigma$ excess in $\mu\mu$
- 3.0 $\sigma$ excess in $ee$

CMS did not report an excess in this channel
Long lived particles

Long lived (LL) particles decaying in flight leaving multiple tracks displaced with respect to the production point.

Heavy LL non-relativistic particles leaving anomalous large energy deposits in inner detector.

Several specialised analyses covering a broad range of lifetimes.

\[ \tilde{g} \text{ R-hadron} \rightarrow g/qq \tilde{\chi}_1^0 ; m_{\tilde{\chi}_1^0} = 100 \text{ GeV} \]

Status: June 2015

95% CL limits. \( \sigma_{\text{SUSY}} \) theory not included
18.4-20.3 fb\(^{-1}\), \( \sqrt{s} = 8 \text{ TeV} \)

ATLAS Preliminary
**Long lived particles**

- **ATLAS Simulation**
- \( \sqrt{s} = 8 \text{ TeV} \)

**Trigger Efficiency**
- \( \mathbf{\nabla} g \rightarrow g\tilde{\chi}_1^0/\bar{q}\tilde{\chi}_1^0, \tau(g) = 10 \text{ ns}, m(\tilde{\chi}_1^0) = 100 \text{ GeV} \)
- \( \mathbf{\Delta} g \rightarrow g\tilde{\chi}_1^0/\bar{q}\tilde{\chi}_1^0, \tau(g) = 10 \text{ ns}, m(\tilde{\chi}_1^0) = 100 \text{ GeV} \)
- \( \mathbf{\Delta} g \rightarrow g\tilde{\chi}_1^0/\bar{q}\tilde{\chi}_1^0, \tau(g) = 1.0 \text{ ns}, m(\tilde{\chi}_1^0) = 100 \text{ GeV} \)
- \( \mathbf{\bullet} \overline{g} \text{ stable} \)
- \( \mathbf{\bigcirc} \overline{\tilde{\chi}}_1^0 \text{ stable} \)

**Search for metastable heavy charged particles**

- Use missing transverse momentum triggers
  - Most efficient for LLPs decaying within detector volume
  - For light neutralinos high momentum jets contribute to energy imbalance

**Parent lifetime**

- \( 10^{-1} \text{ ns} \)
- \( 1 \text{ ns} \)
- \( 10 \text{ ns} \)
- \( 100 \text{ ns} \)

**Decay occurs close to production point**

- **Intermediate case** - decay occurs in inner detector

- **Decays occur beyond calorimeters - similar to stable case**

**Dependence on MET**
Scan of phenomenological MSSM parameter space

- 19 dimensional phenomenological MSSM sampled
- 310,000 models surviving all theory and non-LHC experimental constraints
- interpreted using results from 22 ATLAS run 1 searches
13 TeV previews with 50 ns data

- lepton (2-6 jets) + MET [W control region]
- lepton (6-7 jets) + MET [extrapolating from 5-6 jets]
Conclusions

- An enormous variety of searches undertaken during LHC run 1 covering many different production and decay modes and final states.

- No evidence for physics beyond the SM during run 1 experiments have published many exclusion limits, continuing to constrain SUSY parameter space.

- All eyes are now on run 2: will we find something in the new data? If so will it be SUSY?

- Whatever the new data brings, SUSY provides us with enough diversity to build analyses that push further into the uncovered corners of possibilities.
### ATLAS SUSY Searches* - 95% CL Lower Limits

Status: July 2015

#### Inclusive Searches

<table>
<thead>
<tr>
<th>Model</th>
<th>$e, \mu, \tau, \gamma$</th>
<th>Jets</th>
<th>$E_{\text{miss}}$</th>
<th>Mass limit</th>
<th>Reference</th>
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<tbody>
<tr>
<td>MSUGRA/CMSSM</td>
<td>0-3 e, $\mu$</td>
<td>1-2 t</td>
<td>2-10 jets/3 b</td>
<td>Yes</td>
<td>20.3</td>
</tr>
<tr>
<td>$\tilde{q} \tilde{q}$, $\tilde{g} \tilde{g}$ (compressed)</td>
<td>0</td>
<td>2-6 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>$850 \text{ GeV}$</td>
</tr>
<tr>
<td>$\tilde{q} \tilde{q}$, $\tilde{g} \tilde{g}$</td>
<td>1-3 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>$780 \text{ GeV}$</td>
<td>m($\tilde{q})$=m($\tilde{g})$</td>
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<tr>
<td>$\tilde{q} \tilde{q}$, $\tilde{g} \tilde{g}$</td>
<td>2 $\ell$, (2j/$\ell$)</td>
<td>2 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>$100$-$440 \text{ GeV}$</td>
</tr>
<tr>
<td>$\tilde{q} \tilde{q}$, $\tilde{g} \tilde{g}$</td>
<td>0</td>
<td>2-6 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>$1.33 \text{ TeV}$</td>
</tr>
<tr>
<td>GMSB (f NLSF)</td>
<td>1-2 t</td>
<td>0-1 f</td>
<td>2-6 jets</td>
<td>Yes</td>
<td>20.3</td>
</tr>
</tbody>
</table>

#### Direct searches

| 3rd gen, squark | 2 $\ell$, (2j/$\ell$) | 1 b | Yes | 20.3 | $850 \text{ GeV}$ | m($\tilde{q})$=m($\tilde{g})$ |
| 3rd gen, squark | 2 $\ell$, (2j/$\ell$) | 2 jets | Yes | 20.3 | $1.25 \text{ TeV}$ | m($\tilde{q})$=m($\tilde{g})$ |

#### EW direct

| EW direct | Disapp. trk | 1 jet | Yes | 20.3 | $124$-$361 \text{ GeV}$ | m($\tilde{q})$=m($\tilde{g})$ |

#### Long-lived charged particles

| Direct $\tilde{\chi}_i^\pm$, prod., long-lived $\tilde{\chi}_i^\pm$ | Disapp. trk | 1 jet | Yes | 20.3 | $270 \text{ GeV}$ | m($\tilde{q})$=m($\tilde{g})$ |
| Direct $\tilde{\chi}_i^\pm$, prod., long-lived $\tilde{\chi}_i^\pm$ | e+e-+X | 1 jet | Yes | 20.3 | $482 \text{ GeV}$ | m($\tilde{q})$=m($\tilde{g})$ |

#### Other

| Scalar charm, $\tilde{c} \rightarrow c \tilde{q}^0$ | 2 c | Yes | 20.3 | $490 \text{ GeV}$ | m($\tilde{q})$=m($\tilde{g})$ |

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*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.