Reconstruction techniques in supersymmetry searches in the ATLAS experiment

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on behalf of the ATLAS Collaboration

DIS 2018 – XXVI International Workshop on Deep Inelastic Scattering and Related Subjects
Will not show a lot of limit plots, I'll refer to the coming talks for all the nice limits from the various analyses
The ATLAS detector at the LHC

Tracking Detector

Since Run 1 a new, Insertable B-layer (IBL), has been installed inside the existing b-layer with a mean sensor radius of 3.3 cm.

Covers the range $|\eta| < 4.9$

Jets are reconstructed by applying a jet-clustering algorithm to topological clusters from the calorimeter signal.
Supersymmetry (SUSY) searches in ATLAS

SUSY provides an extremely rich model space

Reflected in the many ongoing analyses targeting various SUSY models

No significant evidence for SUSY
Don’t know the mass scale/nature of the SUSY particles

- stable and meta-stable particles
  - large mass differences
  - small mass differences (compressed)
  - light 3rd gen. squarks
    - boosted objects
    - boosted by ISR jets
    - soft b- and c-jets

For more results on long lived sparticles see Jeanette’s talk later today

Displaced vertices [1710.04901]
Disappearing tracks [1712.02118]
Large ionization losses [Phys. Rev. D 93, 112015 (2016)]
Slow Propagation Velocities [1606.05129]

Jet re-clustering
Recursive Jigsaw Reconstruction
b- and c-tagging

Jets and jet re-clustering

- The standard jet algorithms in ATLAS use a predefined radius parameter, R, to build jets
  - R is roughly the size of the jet in the (η,Φ)-space

- The optimal R is process dependent and scales with the inverse of the momentum under consideration
  - ideally the R parameter would be optimised for each analysis
    - however, each jet configuration must be calibrated, in situ, to account for detector response, pile-up suppression and other experimental effects
      - reason why only a few choices of R (0.4) are used in most analyses in ATLAS
    - a solution is to re-cluster large R jets using the smaller R jets as input
      - the fully calibrated small R jets can make the calibration of the re-clustered large R jets automatically

\[ \Delta R \sim \frac{2m}{p_T} \]
Re-clustering

- large-R jets (R=1.0) built directly from topoclusters from calorimeter cells are available in ATLAS
  - calibrations and corrections done as for small-R jets

large-R jets re-clustered from small-R jets show comparable or better jet mass resolution and uncertainties than calibrated large-R trimmed jets!
Use of large R-jets in SUSY analysis

Top-tagging of boosted tops

• reconstructing the hadronic top-quark decay can provide discrimination against di-leptonic $t\bar{t}$ events
• large R-jets is used to target events where the top quark is produced with a significant boost
  • re-clustering small-R jets into large-R jets with $R = 3.0$
  • radius of each jet is iteratively reduced to an optimal radius to match the $p_T$

\[ R(p_T) = 2 \frac{m_{\text{top}}}{p_T} \]

jet mass:
\[ M_j = \left( \sum_{i \in \text{jet}} E_i \right)^2 - \left( \sum_{i \in \text{jet}} p_i \right)^2 \]

• same method is used to define boosted hadronically decaying W-boson candidates
Use of large R-jets in SUSY analysis

Total jet mass

\[ M_j^\Sigma = \sum_{n \leq x} M_{j,n} \]

A sum over all the large-R re-clustered jets in the event

Typically large in events with as many as four top quarks while the main background is dominated by \( t\tilde{t} \) events with one or two hadronically decaying tops
For more results on searches for gluinos and squarks see Matt LeBlanc’s talk later today.
# Use of large R-jets in SUSY analysis

<table>
<thead>
<tr>
<th>SUSY Production</th>
<th>Final State</th>
<th>Radius Parameter</th>
<th>Data and Energy</th>
<th>Reference</th>
<th>Used for</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, $\tilde{q}\tilde{q}$</td>
<td>0-lepton, jets, $E_T^{miss}$</td>
<td>1.0</td>
<td>36fb$^{-1}@13$TeV</td>
<td><a href="https://arxiv.org/abs/1712.02332">1712.02332</a></td>
<td>To select hadronically decaying W and Z</td>
</tr>
<tr>
<td>$\tilde{t}\tilde{t}$</td>
<td>1 lepton, jets, $E_T^{miss}$</td>
<td>3.0</td>
<td>36fb$^{-1}@13$TeV</td>
<td><a href="https://arxiv.org/abs/1711.11520">1711.11520</a></td>
<td>W- and Top-tagging (2-top events)</td>
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<tr>
<td>$\tilde{g}\tilde{g}$</td>
<td>0-1 leptons, b-jets, $E_T^{miss}$</td>
<td>0.8</td>
<td>36fb$^{-1}@13$TeV</td>
<td><a href="https://arxiv.org/abs/1711.01901">1711.01901</a></td>
<td>Top-tagging (4-top events)</td>
</tr>
<tr>
<td>$\tilde{t}\tilde{t}$, $\tilde{g}\tilde{g}$</td>
<td>0 lepton, b-jets, jets, $E_T^{miss}$</td>
<td>1.2/0.8</td>
<td>36fb$^{-1}@13$TeV</td>
<td><a href="https://doi.org/10.1007/JHEP12(2017)085">JHEP 12 (2017) 085</a></td>
<td>Top and W-tagging</td>
</tr>
<tr>
<td>$\tilde{t}\tilde{t}$, $\tilde{g}\tilde{g}$</td>
<td>1 lepton, b-jets, jets, $E_T^{miss}$</td>
<td>1.2/1.0</td>
<td>3.2fb$^{-1}@13$TeV</td>
<td><a href="https://doi.org/10.1103/PhysRevD.94.052009">Phys. Rev. D 94 (2016) 052009</a></td>
<td>Top-tagging</td>
</tr>
</tbody>
</table>
Recursive Jigsaw Reconstruction (RJR)

For compressed scenarios:

\[ 0 < \Delta m(\tilde{g}/\tilde{q}/\tilde{t}, \tilde{\chi}_1^0) < 200 \text{ GeV} \]

\( E_T^{\text{miss}} \) does not come from the large momentum of WIMPS received from decays, but rather from recoiling against Initial State Radiation (ISR) jets

Rather than relying on «mono-ISR»-signal, RJR tries to separate ISR objects from the sparticle objects.

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<td>0-lepton, jets, ( E_T^{\text{miss}} )</td>
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<td>1711.11520</td>
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<tr>
<td>( \tilde{g}\tilde{g}, \tilde{t}\tilde{t} )</td>
<td>0 lepton</td>
<td>36fb(^{-1})@13TeV</td>
<td>JHEP 12 (2017) 085</td>
</tr>
</tbody>
</table>
Recursive Jigsaw Reconstruction (RJR)

Accomplished with a simple decay view of the event

- CM: centre-of-mass system incl. all visible objects and $E_T^{\text{miss}}$
- ISR: particles not from the sparticle decays
- S: sparticle system
- V: visible decay products
- I: WIMP

Each event is reconstructed by:
1. ignoring the longitudinal momenta of all jets
2. treat $E_T^{\text{miss}}$ as the transverse momentum of I (with zero mass)
3. partition all jets into ISR and V by minimizing the mass of the ISR and S systems
4. Analyse the event kinematics in the transverse view

$p_{TS}^C$: magnitude of the vector summed transverse momenta of all S-associated jets and $E_T^{\text{miss}}$ - evaluated in the CM frame
Recursive Jigsaw Reconstruction (RJR)

The RJR signal regions provides the best sensitivity in regions where $\Delta m(\tilde{g}/\tilde{q}, \tilde{\chi}_1^0) < 50$ GeV, Squark masses up to 650 GeV and gluino masses up to 1 TeV are excluded.
SUSY searches with b/c-tagged jets

- Naturalness considerations suggest that the superpartners of the third generation quarks are the lightest coloured supersymmetric particles
  - may lead to light $\tilde{b}$ and $\tilde{t}$ squarks and therefore produced with relatively large cross-sections at the LHC
  - results in final states with b- or c-jets
SUSY searches with b/c-tagged jets

B-tagging in ATLAS is based on three distinct strategies

1. **Impact Parameter**: exploiting the relatively large life times: $\sim 1.5$ ps, $c\tau \sim 450\mu$m by measuring impact parameters of tracks
2. **Secondary Vertex Finding**: builds secondary vertices within the jets
3. **Decay Chain Multi-Vertex**: exploits the topological structure of weak b- and c-hadron decays inside the jet (reconstruct the full b-hadron decay chain)

The inclusion of the IBL has significantly improved the b-tagging performance in Run 2

Major improvement in c-jet rejection since 2015
SUSY searches with b/c-tagged jets

<table>
<thead>
<tr>
<th>Operating point</th>
<th>c-tagging eff.</th>
<th>b-jet rejection</th>
<th>light-jet rejection</th>
<th>τ-jet rejection</th>
</tr>
</thead>
<tbody>
<tr>
<td>medium</td>
<td>20%</td>
<td>8</td>
<td>200</td>
<td>10</td>
</tr>
<tr>
<td>loose</td>
<td>95%</td>
<td>2.5</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

For more results on 3rd generation squarks see Jovan’s talk later today.

Improvements also in the b-tagging efficiency by exploiting new approaches to multivariate analysis and training samples.
Conclusions

• supersymmetry as an extension to the Standard Model is very well motivated
  – solves the hierarchy problem
  – provides a natural candidate for Dark Matter…
• only drawback is that there has not yet been any significant evidence for it’s existence
• however, SUSY is still alive, we just need to
  – develop more clever methods in the analyses
    • several improvements and new techniques have been developed since LHC Run 1
  – start looking into new territory
    • with more and better understanding of the data we become more sensitive to new regions of phase space
BACKUP
Jets and jet re-clustering

• The jet clustering algorithms in ATLAS uses sequential recombination
  - defines distance metrics $d_{ij}$ (between object $i$ and $j$) and $d_{iB}$ (object $i$ and beam direction)
    - $i$ and $j$ combined into protojet if $d_{ij} < d_{iB}$
    - protojet $i$ defined as jet if $d_{ij} > d_{iB}$
    - process continues until no protojets left

• The optimal radius parameter, $R$, is process dependent and scales with the inverse of the momentum under consideration
  - ideally the R parameter would be optimised for each analysis
    - however, each jet configuration must be calibrated, in situ, to account for detector response, pile-up suppression and other experimental effects
      - reason why only a few choices of R (0.4 and 0.6) are used in most analyses in ATLAS
  - a solution is to re-cluster large R jets using the smaller R jets as input
    - the fully calibrated small R jets can make the calibration of the re-clustered large R jets automatically
calibrated large-R jets removes subjets if

\[ p_T^{\text{subjet}} < f_{\text{cut}} \cdot p_T^{\text{jet}} \]

re-clustering algorithms removes any small radius jet constituent \( j \) of a large R re-clustered jet \( J \) if

\[ p_T^j < f_{\text{cut}} \cdot p_T^J \]
Use of large R-jets in SUSY analysis

**W- and Z-tagging**

- small mass difference between parent SUSY particle and intermediate chargino/neutralino can cause W and Z to have significant $p_T$
  - decay products appear as a single high-mass jet

$$M_J = \left( \sum_{i\in jet} E_i \right)^2 - \left( \sum_{i\in jet} \vec{p}_i \right)^2$$

![Diagram of the process](image)
Use of large R-jets in SUSY analysis

Top-tagging of boosted tops

High top squark masses

\[ m_{\tilde{t}} \sim O(1000 \text{ GeV}) \]

Highly boosted requires two large-R jets (R = 1.2)
Use of large R-jets in SUSY analysis

Top-tagging of boosted tops

High (1000 GeV) top squark masses

Two R = 1.2 re-clustered jets are required and events classified based on jet mass:

- \( m_{\text{jet}} > 120 \text{ GeV} \) : top candidate (T)
- \( 60 < m_{\text{jet}} > 120 \text{ GeV} \) : W candidate (W)
- \( m_{\text{jet}} < 60 \text{ GeV} \) : unclassified (0)

\( m_t - m_{\tilde{\chi}_1^0} \sim m_t \)

High \( p_T \) jets from Initial State Radiation (ISR) jets boost the di-top-squark system

requires also two large-R jets (R = 0.8)
Recursive Jigsaw Reconstruction (RJR) Analyses

- a method for decomposing measured properties event by event to provide a basis of kinematic variables
- events involving invisible weakly interacting particles present a challenge, as their four-momenta are only partially constrained
- this loss of information from escaping particles constrains the kinematic variable construction
- the RJR technique partially mitigates this loss of information by determining approximations of the rest frames of intermediate particle states in each event

**PP**: initially produced sparticles

**P_a, P_b**: assigned to two hemispheres (a and b) and decays to the particles observed in the detector:
- **V**: visible objects
- **I**: invisible objects
Recursive Jigsaw Reconstruction (RJR) Analyses

- the jets are partitioned into the two hemispheres $a$ and $b$ by choosing the grouping which minimizes the masses of the two systems
- the remaining unknowns in the event are then associated with the neutralinos ($I_a$ and $I_b$):
  - masses
  - longitudinal momenta
  - how each contribute to the $p_T^{miss}$
- determined through subsequent minimizations of the intermediate particle masses appearing in the decay tree
- constructs several rest frames for which all relevant momenta are defined and can be used to construct variables (invariant masses, angles between objects etc.)
If $\tilde{q}, \tilde{g}$ are nearly mass degenerate with the $\tilde{\chi}^0_1$

$$E_T^{\text{miss}} \sim -\Delta p_T^{\text{ISR}} \times \frac{m_{\tilde{\chi}^0_1}}{m_{\tilde{q}, \tilde{g}}}$$

Rather than relying on «mono-ISR»-signal, RJR tries to separate ISR objects from sparticle objects.

- $p_T^{\text{CM}}$: the magnitude of the vector-summed transverse momenta of all $S$-associated jets ($|\vec{p}_T^{\text{CM}}|$) and $E_T^{\text{miss}}$ evaluated in the CM frame.

- $R_{\text{ISR}} \equiv \hat{p}_I^{\text{CM}} \cdot \hat{p}_T^{\text{CM}} / p_T^{\text{CM}}$: serves as an estimate of $m_{\tilde{\chi}} / m_{\tilde{q}, \tilde{g}}$. This is the fraction of the momentum of the $S$ system that is carried by its invisible system $I$, with momentum $\hat{p}_I^{\text{CM}}$ in the CM frame. As $p_T^{\text{CM}}$ grows it becomes increasingly hard for backgrounds to possess a large value in this ratio – a feature exhibited by compressed signals.

- $M_{T S}$: the transverse mass of the $S$ system.

- $N_{\text{jet}}^V$: number of jets assigned to the visible system ($V$) and not associated with the ISR system.

- $\Delta \phi_{\text{ISR}}$, $\rho$: the azimuthal opening angle between the ISR system and the invisible system in the CM frame.
# (Meta-)Stable SUSY particles

<table>
<thead>
<tr>
<th>Reconstruction technique</th>
<th>SUSY scenario(s)</th>
<th>Data and Energy</th>
<th>Ref.</th>
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<td>Non-pointing and delayed photons</td>
<td>Gauge-Mediated Symmetry Breaking (GMSB)</td>
<td>20fb⁻¹@8TeV</td>
<td>[Phys. Rev. D. 90, 112005 (2014)]</td>
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<tr>
<td>Displaced vertices</td>
<td>R-hadron models</td>
<td>33fb⁻¹@13TeV</td>
<td>[1710.04901]</td>
</tr>
<tr>
<td>Large ionization losses and slow propagation velocities</td>
<td></td>
<td>3.3fb⁻¹@13TeV</td>
<td>[1606.05129]</td>
</tr>
<tr>
<td>Disappearing tracks</td>
<td>Anomaly-Mediated Supersymmetry Breaking (AMSB)</td>
<td>36fb⁻¹@13TeV</td>
<td>[1712.02118]</td>
</tr>
<tr>
<td>Large ionization losses</td>
<td>mini-split SUSY, AMSB</td>
<td>3.3fb⁻¹@13TeV</td>
<td>[Phys. Rev. D 93, 112015 (2016)]</td>
</tr>
</tbody>
</table>
Disappearing Tracks

- Large improvements in analysis compared with Run1 thanks to the new IBL
  - Run1: sensitive to charginos decaying at radii > 30 cm. (*short tracks*)
  - Run2: sensitive down to radii of ~12 cm. (*tracklets*)

April 15, 2018

Signal: a chargino decaying a measurable distance (> 12 cm) from the interaction point

Backgrounds:
- A hadron undergoing a hard scattering
- Lepton emitting a hard photon
- Random combination of hits forming tracklets

For more results on long lived sparticles see Jeanette’s talk later today

Track/tracklets:
1. **tracks**: reconstructed using standard algorithms (> 7 hits in silicon detectors)
2. **tracklets**: track reconstruction is rerun with looser criteria (≥ 4 hits in Pixel) using only hits not associated to any tracks
   - extrapolated to SCT and TRT and any compatible hits are assigned to the tracklet
   - required to have \( p_T > 5 \text{ GeV} \) and \( |\eta| < 2.2 \)
Large Ionizations Losses

- The average energy loss of a massive, charged particle in matter is expected to follow the Bethe-Bloch distribution.
  - From measurements of $\frac{dE}{dx}$, $\beta\gamma$ can be estimated from...
  - Mass found through $m = \frac{p}{\beta\gamma}$
  - Valid in $0.3 < \beta\gamma < 1.5$
    - Overlaps the expected range of long lived particles produced at the LHC (100 – 1600 GeV)
  - $p_1, ..., p_5$ are calibration constants measured in data using low-momentum pions, kaons and protons.

\[
\frac{dE}{dx}(\beta\gamma)_{MPV} = \frac{p_1}{\beta p_3} \ln(1 + [p_2 \beta\gamma] p_5) - p_4
\]
Slow Propagation Velocities

- charged particles with a speed measurably slower than c can be identified and their mass determined from their measured speed (\( \beta \)) and momentum, using the relation \( m = \frac{p}{\beta \gamma} \)
  - estimation of \( \beta \) from time-of-flight measurements relies on timing and distance information from the tile-calorimeter cells crossed by the extrapolated candidate track

- five cell-by-cell \( \beta \) corrections are applied
  1. minimise the \( \eta \) dependence of \( \beta \) within each cell (shifts of \( \sim 0.05 \) in \( \beta \) at high \( \eta \))
    - actual trajectory of the extrapolated track in each calorimeter cell is used to re-calculate the distance-of-flight
  2. correction on MC to account for timing mismodelling due to imperfect simulation (shifts of \( \sim 0.1 \) in \( \beta \) at high \( \eta \))
  3. compensate for the fact that the readout of the tile calorimeter is optimised for in-time signals (shifts of \( \sim 0.05 \) in \( \beta \) at high \( \eta \))
  4. cell-time smearing to adjust the cell-time resolution in simulation to that in data
  5. uncertainty in the single \( \beta \) measurements is scaled up by \( \sim 12\% \) based on the requirement that the pull distribution to be a unit Gaussian

finally the \( \beta \) associated with the particle is estimated as a weighted average, using the \( \beta \) measurement in each traversed cell and its uncertainty, \( \sigma_\beta \)
Displaced Vertices (DV)

- massive particles with lifetimes in the ps to ns range could decay in the inner tracker volume of ATLAS
  - the decay products often contain several electrically charged particles, which can be reconstructed as tracks
  - a displaced vertex can be reconstructed by using dedicated tracking and vertexing techniques

Displaced tracks and vertices:
- standard track reconstruction puts relatively tight constraints on the transverse ($d_0$) and longitudinal ($z_0$) impact parameters (IP) of track candidates
  - $|d_0| < 10$ mm and $|z_0| < 250$ mm
- an additional large-radius tracking (LRT) algorithm with looser criteria is used to reconstruct DV
  - using hits not associated to track reconstructed by standard algorithms
  - increased IP cuts: $2 < |d_0| < 300$ mm and $|z_0| < 1500$ mm
  - relaxed criteria of hits shared with several tracks

Backgrounds:
- hadronic interactions in material rich regions – excluding 42% of the fiducial detector volume
- veto vertices matching track multiplicities and reconstructed masses expected from $K_S^0$ and $\Lambda^0$ decays

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Non-Pointing and Delayed Photons

- photons stemming from long lived particle decays may show up in many SUSY scenarios
  - these photons may then be non-pointing and/or delayed

### non-pointing photons:

- the flight direction of photons are measured precisely using the three different longitudinal segments of the LAr EM calorimeters
- the direction is compared with the direction back to the PV
  - separation of the direction along the beamline defines $|\Delta z_\gamma|$

The expected pointing resolution as a function of $|z_{\text{origin}}|$ for MC (using MC gen. level information to determine $z_{\text{origin}}$) and $Z \rightarrow ee$ events (using $z_{PV}$ as $z_{\text{origin}}$)

- arrival time of the photon can be measured by the LAr calorimeter and defined as the the arrival time $t_\gamma$ of a photon
  - $t_\gamma = 0$: expected from prompt photons
  - $t_\gamma > 0$: photons from non-prompt LLP decays

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In a pure wino LSP model, for $\tau_{\tilde{\chi}_1^\pm} \sim 0.2$ ns, i.e. $\Delta m(\tilde{\chi}_1^+, \tilde{\chi}_1^0) \sim 160$ GeV, charginos of a mass up to 460 GeV are excluded.