Reconstruction techniques in Supersymmetry searches with the ATLAS detector

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Abstract. Many supersymmetric scenarios of the Standard Model feature final states which are difficult for standard particle reconstruction. The production of massive sparticles can for example lead to the production of boosted quarks or vector bosons. At the same time, transitions between nearly mass-degenerate sparticles challenges the standard event reconstruction because of the presence of very soft leptons or jets. This contribution to the conference proceedings will review the application of innovative reconstruction techniques to supersymmetry searches in ATLAS.

1. Introduction
The ATLAS detector [1] is a multi-purpose detector situated at the Large Hadron Collider (LHC) in Geneva. The detector consists of several components. Starting closest to the point of collision we have an inner-tracker, which is surrounded by a solenoid field. This part of the detector performs a momentum measurement on charged particles. Surrounding the inner-tracker there are electromagnetic and hadronic calorimeters for energy measurements. All of this is surrounded by a muon spectrometer, in a toroidal magnetic field, which does a final measurement on muon momentum and identification. All of these components of the detector try to identify the types and properties of all particles produced in the collision as accurately as possible. Using this information we can determine which particles were created and we can test hypotheses on what happened at the interaction point.

Supersymmetry predicts a lot of different scenarios. All of these scenarios show a very distinct pattern in our detector, where we need to apply the correct reconstruction techniques to gain sensitivity. Parts of the standard ATLAS reconstruction do not provide the required sensitivity. So in order to dig into these more difficult areas of phase space dedicated efforts are required. These reconstruction techniques are discussed in these conference proceedings of ICPPA 2018 (Moscow).

2. Small mass gaps between Supersymmetric partners
A dedicated effort has been made by the ATLAS experiment towards the reconstruction of low transverse momentum ($p_T$) leptons. The need for this is illustrated using the Feynman diagram shown in Figure 1. If the mass gap between the two supersymmetric particles $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$, $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$, is small, the W and Z bosons will be very off-shell, resulting in low $p_T$ leptons or jets. Since it is hard to gain sensitivity on low $p_T$ jets due to QCD background, and we need to be able to reconstruct the vector bosons, these are usually reconstructed from leptons.

2.1. Low $p_T$ leptons
Electrons are reconstructed down to 4.5 GeV [2], using topologically formed clusters and dedicated Bremsstrahlung correction. Muons are reconstructed down to 3 GeV, as can be seen in Figure 2. Since the
average energy loss in the calorimeter is already 3 GeV, dedicated algorithms are being used to get the most out of the detector. Current published ATLAS supersymmetry papers include muons reconstructed down to 4 GeV.

Further improvements are possible with this new lower $p_T$ threshold. However, this will also lead to extra backgrounds from fake leptons in this $p_T$ regime. Fake leptons are leptons which our reconstruction algorithms judge as leptons coming directly from our collision but are actually coming from for example heavy flavour decays, a photon or are particles that get misidentified.

In Figure 3 we can see the inclusion of low $p_T$ leptons in an analysis. As can be seen the signal actually peaks at low $p_T$ so this gives us additional sensitivity. Also, in the low $p_T$ the main background is from fake/non prompt which should be a reducible background. So key to improving the performance lies with lepton isolation and impact parameters. New ideas can be explored such as using a Boosted Decision Tree (BDT) for isolation. Such a BDT would take as input measurements like energy deposits and charged-particle tracks in a cone around the lepton direction.

3. Large mass gaps between Supersymmetric partners

Next to the reconstruction of low $p_T$ leptons, there is also a dedicated effort within ATLAS towards the reconstruction of boosted topologies and decays with multiple quarks. These scenarios arise from large mass gaps between supersymmetric partners. An example of such a process can be seen in Figure 4.

The gluino is known to have a mass of at least a few TeV causing the resulting massgap $\Delta m(\tilde{g}, \tilde{\chi}_1^0)$ to be very large. Because of this the top quark pairs will be very boosted. Depending on how boosted the system is, the jets originating from the top quark decays will overlap. In order to be able to reconstruct
these overlapping jets special reconstruction techniques need to be used, such as reclustering. For other analyses there are special reconstruction algorithms needed to see if jets originate from b quarks, which is called flavour tagging and in this case b-tagging. Finally ATLAS is starting to look into tagging other types of flavours of quarks such as c quarks.

3.1. Reclustered jets

"Standard" jet finding in ATLAS uses the anti-Kt algorithm. This algorithm takes as one of the input parameters the radius of the jet, in the standard case this is 0.4. However, because of the boosted scenario that we have in Figure 4, the jets will start to overlap and merge into one big "fat" jet. This fat jet exceeds the standard radius of 0.4. In standard reconstruction we would lose these jets and we need to come up with a new strategy. For this problem two solutions can be proposed:

(i) Use a larger radius parameter
(ii) Cluster existing calibrated 0.4 radius jets into a larger jet

The second option is called reclustering and as we can see from figure 5 has a lower jet calorimeter mass resolution, which means it outperforms the larger radius parameter. This is because reclustering can use the detailed calibrations and uncertainties from 0.4 jets, which allows more flexibility in the parameters of large R jets because no dedicated calibration is needed.

Reclustering is being used in several ATLAS supersymmetry analyses where we have boosted topologies. For the analysis of $\bar{g}g$ production decaying into $t\bar{t}$, the limit plot can be seen in Figure 6. In the lower right corner of the diagram, where we have a high $\bar{g}$ mass and low $\chi^0_1$ mass, reclustering significantly improves our capability to set limits.

3.2. Flavour tagging

In cases where we have decays with multiple b quarks, we need to be able to tag these jets as a b-jet. BDT’s are being used to determine if jets originate from a b quark by using the impact parameter, secondary vertex finding and decay chain multi-vertex algorithms. Also significant improvements can be seen with the installation between Run 1 and Run 2 of the Insertable B-Layer (IBL), an extra layer in the inner-tracker which sits even closer to the beam-line than the previous closest tracking layer. This
The upgrade allows us to know even more about the origin of particles in the detector because it is so close to the collision, these improvements can be seen in figure 7.

Figure 7. The light-flavour and c jet rejection in bins of jet $p_T$ for the MV1c b-tagging algorithm using the Run-1 detector and reconstruction software (blue) compared to the MV2c20 b-tagging algorithm using the Run-2 setup (red) [7].

3.3. C-tagging

Another more advanced technique which is currently under construction aims to tag jets which originate from a c quark. This is more difficult because c quarks show less distinct features compared to light quarks than b quarks do. In order to achieve reasonable efficiencies c-tagging algorithms use additional variables compared to b-tagging, such as the invariant mass of secondary tracks, secondary track rapidities, distance from primary to secondary vertex and fraction of jet track energy carried by secondary tracks. A recent result which focuses on the decay to c quarks is shown in figure 8 which targets $\tilde{t} \rightarrow c\tilde{\chi}^0_1$.

4. $E_T^{miss}$ reconstruction

Missing transverse momentum, $E_T^{miss}$, is an important measurement for supersymmetry because it is indicative of $\tilde{\chi}^0_1$ (neutralino’s) being produced in the collision that escape detection. $E_T^{miss}$ gets calculated as a function of all the measured particles in a collision. By taking the $p_T$ sum of all the particles in the detector and by requiring momentum conservation we can test if particles escaped the detector undetected. Because the $E_T^{miss}$ estimate depends on the measurement of all the other particles, it usually has a large uncertainty and its accuracy is much dependent on particle resolutions. Because $E_T^{miss}$ is such an important measurement within supersymmetry we try to reconstruct this as accurately as possible. In the next part we discuss fake $E_T^{miss}$ and $E_T^{miss}$ significance.

4.1. Fake $E_T^{miss}$

Fake $E_T^{miss}$ can arise from interacting particles that escape the acceptance of the detector, are inaccurately reconstructed, or fail to be reconstructed all together. For example certain analyses, such as those targeting figure 9, from which we expect the backgrounds to have $E_T^{miss} = 0$, do get fake $E_T^{miss}$, usually due to QCD backgrounds, that are difficult to model, have large cross-sections, and contain jets which have large resolution effects. All of this results in large fake $E_T^{miss}$, however we have a technique to cope with that, $E_T^{miss}$ significance.
4.2. $E_T^{\text{miss}}$ significance

The energy resolution in the calorimeter can be estimated using $\sqrt{\sum E_T}$, where $\sum E_T$ is the measured energy in the collision. Using this we can now define an event-based $E_T^{\text{miss}}$ significance by the following equation,

$$S = \frac{E_T^{\text{miss}}}{\sqrt{\sum E_T}}.$$ (1)

However, this puts the same weight on the resolution of all the particles in the collision. While we can for example reconstruct leptons with much better resolution than jets. We can exploit this extra information by not looking at the total summed energy in the collision but by taking the resolution of each particle into account separately. The object-based $E_T^{\text{miss}}$ significance indicates the degree to which the reconstructed $E_T^{\text{miss}}$ agrees with momentum resolution and particle identification efficiencies, by checking if the log-likelihood ratio that the reconstructed $E_T^{\text{miss}}$ is consistent with the hypothesis of 0 real $E_T^{\text{miss}}$.

The comparison between these two approaches can be seen in Figure 10 in simulated $Z \to ee$ and $ZZ \to ee\nu\nu$ samples with a $Z \to ee$ selection. From this figure we can see that the performance of the object-based $E_T^{\text{miss}}$ significance is much better and this has been used in several supersymmetry analyses such as figure 11, where we can remove a lot of background where real $E_T^{\text{miss}} = 0$.

5. Other dedicated reconstruction algorithms

Supersymmetry has many unknowns, for example in many of the Feynman diagrams in these proceedings we see two $\tilde{\chi}_1^0$ particles escape the detector. However, we do not know the mass of this $\tilde{\chi}_1^0$ particle and we only have one quantity which defines what has escaped our detector which is $E_T^{\text{miss}}$.

5.1. $m_{T2}$

We measure one variable $E_T^{\text{miss}}$, but this is actually composed out of two particles, these two particles escape the detector undetected, the masses of these particles are unknown, the masses of their parent particles are unknown, the center-of-mass energy of the collision is not known and the boost along the beam axis is not known. In the $m_{T2}$ algorithm we try to disentangle the $E_T^{\text{miss}}$ and find out which part belongs to each of the $\tilde{\chi}_1^0$. The $m_{T2}$ algorithm does this by minimizing the following equation,
Figure 12. Distribution of $m_{T2}$ in a supersymmetry analysis showing the cut-off at the $\tilde{\chi}_1^0$ mass [4].

$$m_{T2}(\chi) = \min_{E_{T}^{\text{miss}}(1)} \left[ \max \left\{ m_{T2}^{(1)}(p_{T}^{(1)}, E_{T}^{\text{miss}}(1)), m_{T2}^{(2)}(p_{T}^{(2)}, E_{T}^{\text{miss}}(2)), \tilde{\chi}_{1}^{0} \right\} \right],$$

which takes as input the $p_{T}$ of visible particles, the $E_{T}^{\text{miss}}$ and an assumption on the $\chi$ mass. Using this we can get a clean cut-off around the mass of our expected $\tilde{\chi}_1^0$ as can be seen in figure 12.

5.2. Recursive jigsaw

Recursive jigsaw is a collection of approaches expressing masses as a function of unknowns, and then maximizing or minimizing, just like in the $m_{T2}$ algorithm. Using measured event properties rest frames of intermediate particles are approximated in a "decay tree", see Figure 13. In the case where two sparticles (labeled PP) are produced, they are assigned to two hemispheres (Pa and Pb) and then decayed to the particles observed in the detector with V denoting visible objects and I invisible objects.

Within the invisible groups: for example masses and longitudinal momenta give information about how they contribute to $E_{T}^{\text{miss}}$. Recursive jigsaw determines these unknowns by identifying the smallest Lorentz invariant function of the visible particles four vectors that ensures the invisible particle mass estimators remain non-negative. In each of these newly reconstructed rest frames, all relevant momenta are defined and can be used to construct a set of variables such as multi-object invariant masses and angles between objects. Recursive jigsaw thus gives a new basis of observables based on energies and momenta of objects in these frames.

6. Conclusions

These conference proceedings describes how dedicated reconstruction algorithms are being used to push into more extreme parts of supersymmetry phase space. Many new ideas are presented such as low $p_{T}$ leptons, BDT’s for isolation, object based significance and recursive jigsaw reconstruction. Full run 2 results are to come from ATLAS supersymmetry searches on these challenging signatures.

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