# Part II Particle and Nuclear Physics Bonus Problems: Searching for supersymmetry with ATLAS

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This problem sheet explores a search for electroweak supersymmetry in the proton-proton collision data recorded by ATLAS in 2015–2018 [1].

## 1 Motivation

One of the main purposes of the LHC is to search for new physics beyond-the Standard Model (SM, BSM). The enormous energies in LHC proton-proton collisions allow for the creation of many particles, up to TeV scale masses. Hopefully, this will included particles that aren't described by the SM, but do allow us to explain the workings of the universe more comprehensively. The first popular BSM model to be constructed is Supersymmetry, a mathematically elegant class of theories that could solve two major issues with the SM. Therefore, a lot of time is spent searching for the production of supersymmetric particles (sparticles) in the LHC data - for example that recorded by the ATLAS detector.

1. What are the major problems with the SM? These can either be patterns in the SM that aren't understood, or observed phenomena that aren't described.
2. What are the two problems with the SM that Supersymmetry could solve? How?
3. Summarise what Supersymmetry is.
4. Why do we know that Supersymmetry must be a broken symmetry?

## 2 Introduction and Detector signature

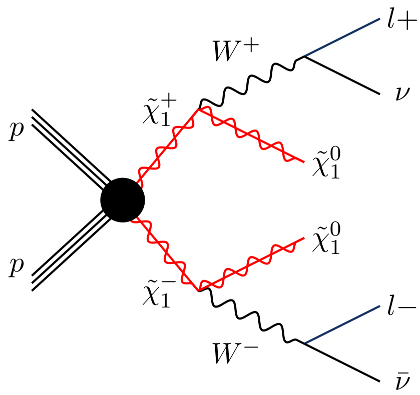
One example of a recent search for Supersymmetry is ATLAS is described in [1]. This is a search for 'electroweak' supersymmetry, which just means the sparticles are produced through electroweak interactions. Electroweak supersymmetry processes have a relatively very weak production cross section, so this kind of search is very challenging! This primarily searches for 'pair-production' of charginos ($\tilde{\chi}_1^{\pm}$), which each decay via a SM W-boson into a neutralino ($\tilde{\chi}_1^0$). We choose a final state where the W bosons each decay to either an electron or muon (and neutrino), since a leptonic signature is cleaner to detect and has a lower background. In R-Parity conserving supersymmetry, the neutralino is stable[1], so does not decay any further. In Supersymmetry, the sparticle masses are free parameters, so our search will look for a variety of masses for the chargino and neutralino.

The process we look for is shown in the diagram in Figure 2[2]. There are several options for the part of the diagram hidden in the blob, all of which must be summed over to properly calculate the Matrix element. One option is that a quark from one proton annihilated with an antiquark from the 2nd proton to produce a Z boson that can decay into the chargino pair.[3]

[1]And constitutes a Dark Matter candidate!

[2]Note the blob part isn't really a proper feynman diagram, just a representation that several things could happen and it's less interesting than the rest of the process. I do not recommend using blobs in your exam

[3]The gluons that hold quarks together in the proton can make $q\bar{q}$ pairs in the proton, this is part of the 'parton model' if you want to look it up.

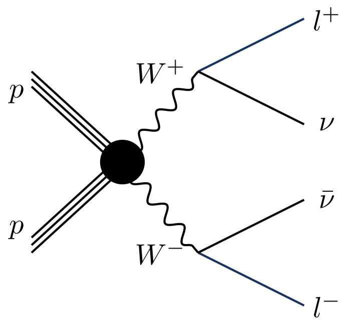



To conserve charge, the two leptons produced in the supersymmetric decay will be oppositely charged. The neutrinos and neutralinos will escape ATLAS undetected, leaving a signature of missing transverse momentum ($p_{\mathrm{T}}^{\mathrm{miss}}$) (transverse = transverse to the proton beam axis). Note the missing transverse momentum is the total vector sum of the transverse momentum of our undetectable particles, and is measured by calculating the vector sum of the transverse momentum of particles we can measure. Thus our final state to detect is two oppositely-charged leptons ($ee$, $e\mu$, or $\mu\mu$) plus $p_{\mathrm{T}}^{\mathrm{miss}}$ as shown in the feynman diagram in Figure 2.

1. Would the cross section for electroweak production of particles/sparticles be higher or lower than strong production?
2. How does the cross section for this supersymmetry process depend on chargino and neutralino masses?
3. Draw the detector signature for the supersymmetry process for each of our three lepton-flavour options. Why do electrons and muons behave differently in the detector?
4. Why can't ATLAS detect neutrinos? How can other experiments detect them?
5. Given that we can't be sure what portion of proton momentum is carried by the interacting quarks, why must we measure the missing transverse momentum rather than the total missing momentum? Would we be able to measure the total mising momentum in a lepton collider?

## 3 Backgrounds

To search for the supersymmetric process, we first pick data events with its detector signature. However, some SM processes will also have this detector signature, and thus also enter into our selection of data events. We have to use other information about the events to discriminate between our supersymmetry signal and SM backgrounds. Ideally we want to find a subset of data events (called a 'signal region') which has a maximal signal to background ratio of events, to maximise our sensitivity, and it is within this signal region that we actually perform our search. The main SM background here is WW production, as illustrated in the Feynman diagram in Figure 3:



In our proton-proton collisions, the quarks in the two protons that aren't involved in our supersymmetric process can also be detected, as jets, although these will often carry a lot of the momentum of the protons and thus have trajectories too close to the beam axis to be within detector acceptance. Alternatively, one of the quarks in our supersymmetry process could radiate a gluon before interacting, adding a jet to our event. To increase the number of expected supersymmetry events in our signal region, without increasing the amount of relative SM background too much, we can allow for one jet in our final state.

There are also two other key SM processes that have our detector signature: ZZ production (where one Z decays to two leptons and the other to two neutrinos), and $t\bar{t}$ production. However we can reduce these quite effectively. $t\bar{t}$ events will have jets initialised from b-quarks in the final state (b-jets). These will contain B hadrons, which have a shorter lifetime than light mesons like the pion. Thus, the B hadrons will probably decay inside the tracker, allowing us to differentiate and 'tag' b-jets from other jets with $70-80\%$ efficiency. We can require that we have no b-tagged jets in our signal region to remove a lot of the $t\bar{t}$ background.[4]

1. One way to produce WW in proton-proton collisions is $q\bar{q} \to WW$. Draw the leading order feymann diagram for this process. What flavours of quarks would give the highest cross section here?
2. Theoretically, what is the ratio between $ee : e\mu : \mu\mu$ final states for both the supersymmetry and WW processes?
3. We could also get WW by producing a Higgs boson that decays into it. Why is this process much rarer than directly producing WW? If we wanted to observe Higgs production to measure the Higgs boson mass, why would it be better to look for $H \to ZZ$ rather than $H \to WW$?
4. What do we mean by a jet? Why can we only detect jets, rather than quarks and gluons individually?
5. One of the most common consitutents of a jet is the $\pi^0$. This will decay very quickly to 2 photons[5]. Show that this $\pi^0$ decay is allowed from Energy/Montum conservation but not $\pi^0 \to \gamma$. Why is the decay $\pi^0 \to \gamma* \to e^+e^-$, where the photon is virtual, still not allowed?
6. If we produced a top quark in a proton-proton collision, how/why we be able to tell it apart from other quark species?
7. In the process $t \to Wq$, why is $q$ almost always a b quark?
8. Given that the b-quark is much heavier than u,d,c,s quarks, why would the B-hadrons have a shorter lifetime than hadrons made from lighter quarks?

# 4 Event selection

To get a signal region as rich as possible in our supersymmetric signal events, we need to find kinematic variables that discriminate between the supersymmetry and WW events. One obvious example is the amount of $p_{\mathrm{T}}^{\mathrm{miss}}$ present, since for the supersymmetric process, this also contains two neutralinos. Another difference is the supsersymmetric process has two heavy charginos decaying first, suggesting we can get discrimination by trying to reconstruct invariant masses from the final decay products. Since we cannot obtain the momenta of each particle in the $p_{\mathrm{T}}^{\mathrm{miss}}$, only the total transverse component, we cannot fully reconstruct the masses of our decaying particles. However, we can define a 'transverse

[4]Note in the paper, several other SM processes are included in the background, these are either rare or match our detector signature as a result of an object being mismeasured or missed (from being outside detector acceptance).

[5]so no track will be left, just two EM calorimeter showers

mass' for a 2-body decay from just looking at the x and y components of the momentum (defining the z direction to be the beam direction) and energy as so:

$$M_{\mathrm{T}}^2 = (E_{\mathrm{T},1} + E_{\mathrm{T},2})^2 - (\vec{p}_{\mathrm{T},1} + \vec{p}_{\mathrm{T},2})^2 \tag{1}$$

$$E_{\mathrm{T},1}^2 = m_1^2 + (\vec{p}_{\mathrm{T},1})^2 = E_1^2 - (\vec{p}_{\mathrm{z},1})^2 \tag{2}$$

This transverse mass provides a lower bound on the mass of the decaying particle. Since our events have multiple particles in in the $p_{\mathrm{T}}^{\mathrm{miss}}$, we cannot simply calculate the transverse mass well, but we can construct more a more complex transverse mass based variable called $m_{\mathrm{T2}}$. $m_{\mathrm{T2}}$is defined to provide a lower bound on the mass of a pair-produced particle that decays semi-invisibly. For the case of our WW background, this variable minimises over the various ways to split the $p_{\mathrm{T}}^{\mathrm{miss}}$ between the two neutrinos, such that we can construct a lower bound on the W-boson mass. If we plot the value of $m_{\mathrm{T2}}$ for all of our events, the distribution will have an endpoint at the W-boson mass (smeared a bit due to finite detector resolution and the W possibly being off-shell). However, calculating this variable for our signal will instead have an end-point at the mass-difference between the chargino and neutralino. So if we require our subset of data events to have values of $m_{\mathrm{T2}}$ higher than the W-boson mass, we can remove a lot of background events, and gain sensitivity to supersymmetry models where the chargino and neutralino have a large mass difference. Note that in the paper we produce several signal regions, each with a given range of $m_{\mathrm{T2}}$, and thus each with sensitivity to a different set of supersymmetric particle masses.

1. What would we need to measure from our final state particles to reconstruct the masses of the decaying W-boson and Chargino?
2. Show that the transverse mass constructed for a two-body decay will always place a lower bound on the mass of the decaying particle ($m^2 \geq M_{\mathrm{T}}^2$).
3. How could we reduce the amount of the ZZ background in our dataset? Are there any other particles that could decay directly to two leptons? Are there any other particles that could decay directly to two neutrinos?

## 5 Results

To do the search, we perform a statistical test to see which of two hypotheses is most consistent with the data yield in our signal regions, using a likelihood ratio. To claim a discovery of this supersymmetric process, the data would need to be far more consistent with the 'supersymmetry+SM' hypothesis, than the 'SM-only' hypothesis. The exclude the existence of this specific supersymmetric model, we would need the converse. These hypotheses are obtained by simulating the supersymmetry and SM processes in the LHC proton-proton collisions, and simulating how the detector would respond to them[6].

At the simplest level, in each of our signal regions, we have:

1. the number of data events observed: $N_{\mathrm{obs}}$
2. the number of events expected in our SM-only hypothesis $N_{\mathrm{SM}} \pm Err$
3. the number of events expected in our SM+supersymmetry hypothesis $N_{\mathrm{SUSY}} \pm Err$. This will vary for each of our sparticle masses tested.

[6] A lot of the paper talks about 'control regions' and 'validation regions'. These are other subsets of data pure in a given SM background process, where we check the simulation does a good job of modelling the data. If there is any disagreement we can use the control regions to define a scale factor to apply the simulated background yield to match the data better. We check that this scaling works in the validation regions.

And we work out which of the expected values is more consistent with data, and to what statistical significance (given the uncertainties). We statistically combine the results in all of the signal regions, to get our overall result of whether supersymmetry is excluded or discovered for each of the masses tested.

We can be more confident about which hypothesis is more consistent with data, if the *Err* is lower. This can be achieved either by having more data/simulations in the signal regions to reduce the statistical uncertainty, or having a detector with better resolution and simulations that are more accurate, to reduce the systematic part of the uncertainty.

We can also be more confident if the two expected values are more different, which will happen if the expected number of supersymmetry events in the signal region is increased. This can be done by designing our signal region better, finding smarter ways to discriminate between the supersymmetry and SM events so that we maximise our supersymmetry/SM event ratio. It can also be done by looking for a signal with a larger cross section, which in this case means testing supersymmetry models with lighter masses.

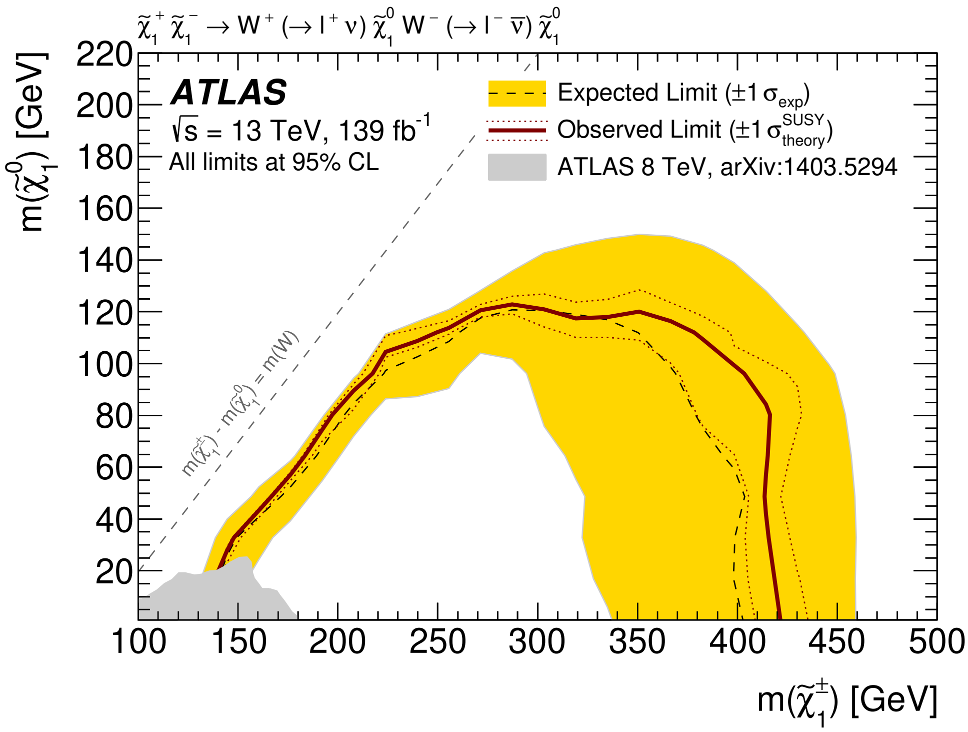



Figure 1: Exclusion limits on our supersymmetry model, as a function of chargino and neutralino masses.

In this search, we unfortunately didn't find evidence of supersymmetry, but did make world-leading limits on what supersymmetric sparticle masses are excluded for this process[7]. The exclusion limit we obtained is shown in Figure 1.

The area inside the solid red line represents sparticle masses that are excluded for this process, i.e. the data disagreed sufficiently well with the SM+supersymmetry hypothesis relative to the SM-only hypothesis that we can be sure they don't exist. Outside of the red line, we can't be sufficiently sure about which hypothesis is favoured to draw a conclusion, so these supersymmetrics models could still exist. The black expected line shows what the expected sensitivity of the search would be if the data looked exactly like the SM simulation[8]. The large yellow errorbar includes all of the uncertainties on the SM background hypothesis: systematic detector uncertainties, uncertainties on the accuracy and precision of the simulation, and statistical uncertainty. The dashed red errorbar on the observed limit comes from the theoretical uncertainty on the supersymmetric process cross section in simulation.

[7]Excluded here means excluded from potentially existing

[8]Where the observed limit is slightly stronger than the expected limit, there was a statistical downward fluctuation in the observed data relative to the SM expectation.

1. The limit where the mass difference between the two sparticles is equal to the W boson mass is shown in grey. Why would we not expect this search to be able to exclude any models to the left of this line?
2. Why do we observe that we our sensitivity drops as the chargino mass increases?
3. The exclusion limit from a Run-1 ATLAS search is shown in the grey blob. This previous search was performed using protons colliding at $\sqrt(s) = 7\,\text{TeV}$, whereas our new search was performed at $\sqrt(s) = 13\,\text{TeV}$. Assuming that the quarks in our supersymmetric process carry 10% of their proton's energy, what is the maximum mass of charginos that could be produced at each of these centre-of-mass energies?

## References

[1] ATLAS collaboration. Search for electroweak production of charginos and sleptons decaying into final states with two leptons and missing transverse momentum in $\sqrt{s}$=13 TeV pp collisions using the ATLAS detector. *Eur. Phys. J. C*, 80:123, 2019, 1908.08215.