ATLAS CP developments

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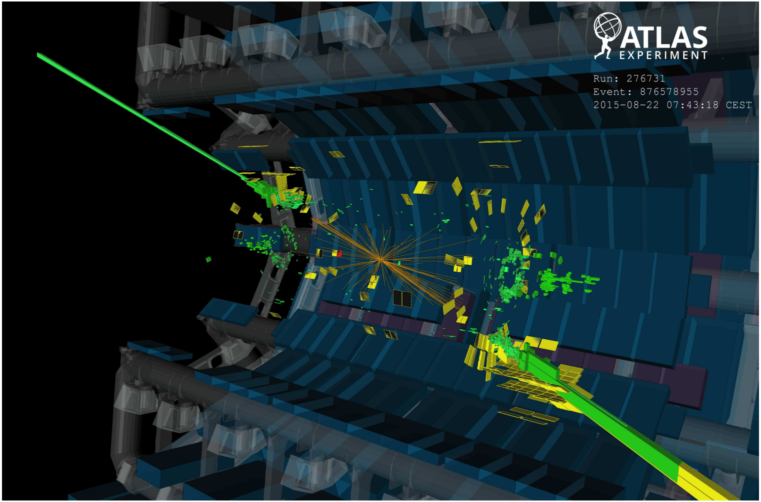
(Re)interpreting the results of new physics searches at the LHC
2nd April 2019



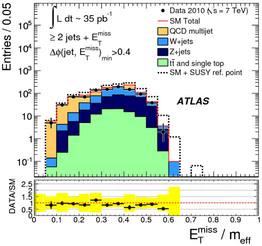
Introduction

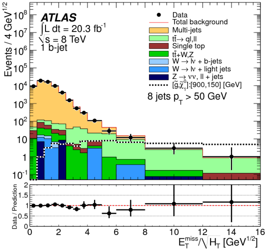
- There is a huge amount of work going on within the collaborations to improve the understanding of the detector such that the uncertainties on the calibrations and efficiencies of all the different physics objects are improved.
- Additionally there are strong efforts to mitigate the effects of pile-up that are becoming more and more significant as the LHC manages to deliver higher and higher luminosities.
- It is obviously not possible for me to cover all the activities in ATLAS so I will focus on a few that will be more significant for searches so are relevant for this workshop (and that are from the JetEtmiss group);
    - $E_{\mathrm{T}}^{\mathrm{miss}}$ Significance
    - DNN Top Tagging
    - Particle Flow Jet Reconstruction
    - Jet Energy Resolution - measurement and understanding

$E_{\mathrm{T}}^{\mathrm{miss}}$ Significance

$E_{\mathrm{T}}^{\mathrm{miss}}$ Significance

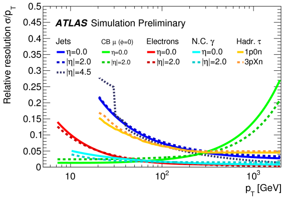
- Throughout the ATLAS search program analyses have cut on the missing transverse energy to separate SM backgrounds from potential new signals with weakly interacting new physics.
- They have also cut on a variety of variables that approximate the significance of this $E_{\mathrm{T}}^{\mathrm{miss}}$
- The idea being that the harder the objects are the more accurate we are in measuring their momenta (fractionally) but the balance between these measured objects will generate fake $E_{\mathrm{T}}^{\mathrm{miss}}$.

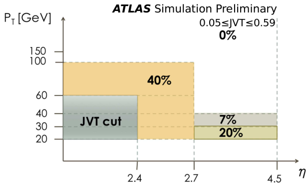




E_T^{miss} Significance

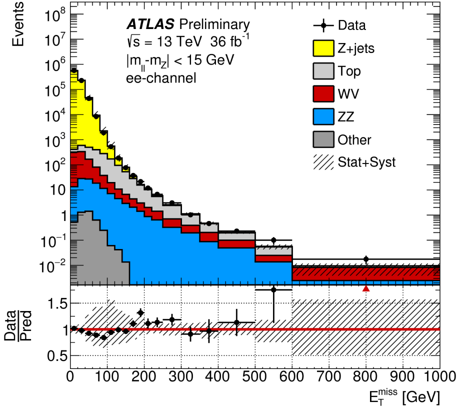
- We now have a tool that computes the significance of the E_T^{miss} based on the actual objects observed in the event.
- The resolutions of all the hard objects are taken into account - including their directions!
- Additional terms are inserted for jets with a high probability of being a pile-up jet.
- Finally there is a term for the measurement of the soft activity in the event.
- It is important to note that this is taking into account the direction of the E_T^{miss} and the significance is the log-likelihood ratio of the consistancy with the real E_T^{miss} being non-zero to zero.

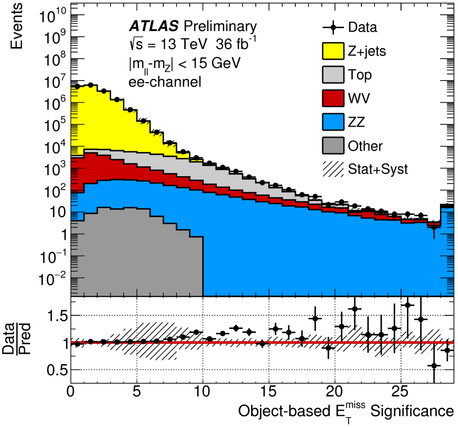




E_T^{miss} Significance

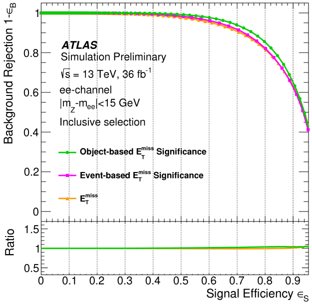
- Looking at the data-to-MC agreement in a selection of $Z \to ee$ events show good modeling of this variable.

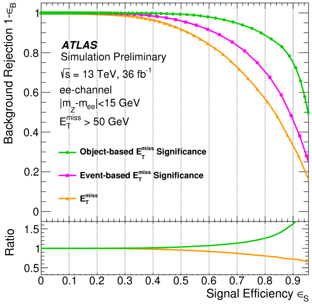




$E_{\mathrm{T}}^{\mathrm{miss}}$ Significance

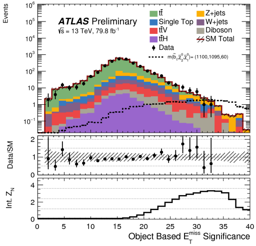
- Within the performance group we look at the separation between $Z \to ee$ and $ZZ \to ee\nu\nu$.
- We find that this new variable is slightly more discriminant.
- If a prior cut on $E_{\mathrm{T}}^{\mathrm{miss}}$ is applied (as would be usual in an analysis) the improvement is substantial.

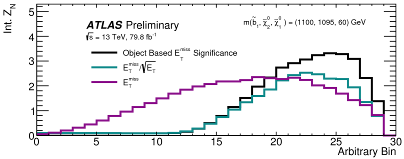




E_T^{miss} Significance

- This was developed last spring/summer so has now been implemented in searches.
- It has been used in both a search for sbottom pair production and in an EW SUSY search.
- This shows the wide applicability of this analysis tool / variable.
- The sbottom search also showed the gains quantitively.
- We are discussing how such a variable could be approximated at truth level for re-interpretation...

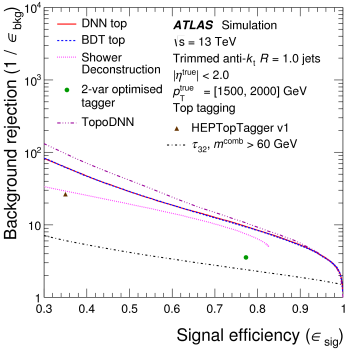




DNN Top Tagging

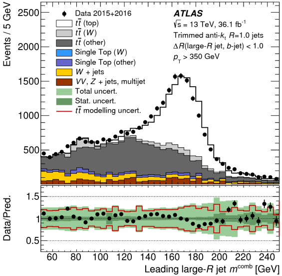
DNN Top Tagging

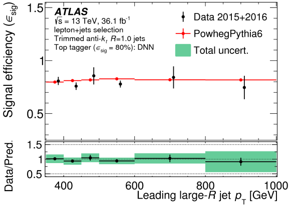
- Machine learning has arrived in the field of performance.
- Previously ATLAS searches used 2-variable taggers - mass and τ_{32}.
- Putting O(10) variables into a BDT or DNN yields significant improvements.
- We are gaining a factor 4 in background rejection for typical signal working points!



DNN Top Tagging

- This does bring a complication as we cannot propagate uncertainties on the inputs to the DNN as the correlations bewteen sub-structure variable modeling is not known.
- Therefore we have developed techniques to measure the efficiency in data.
- Semi-leptonic $t\bar{t}$ gives a pure enough sample prior to tagging that the mass spectra can be fit before and after tagging simultaneously to extract the efficiency scale-factors and uncertainties.





DNN Top Tagging

- As we measure the efficiency we can release this to the public for re-interpretation – we even sometimes have flat efficiency working points where the distribution is trivial.
- However, this is for a very specific truth definition;

4.2 Jet labelling

As the aim of this study is the evaluation of the performance of jet tagging algorithms, the labelling of the particle that initiated the jet is of particular importance. For signal jets, this labelling is based on the partonic decay products of the particle of interest (W boson or top quark) in a three-step process. First, reconstructed jets are matched to truth jets with a matching criterion of $\Delta R(j_{\text{true}}, j_{\text{reco}}) < 0.75$. Next, those truth jets are matched to truth W bosons and top quarks (W, t) with a matching criterion of $\Delta R(j_{\text{true}}, \text{particle}) < 0.75$. Finally, the partonic decay products of the parent W boson or top quark (two quarks for hadronically decaying W bosons and an additional b-quark) are matched to the reconstructed jet. A reconstructed jet is labelled as a W-boson or top-quark jet if the parent particle and all of its direct decay products are contained within a region in (η,ϕ) with $\Delta R < 0.75 \times R_{\text{jet}}$, where R_{jet} is the jet radius. In the case of W bosons, this means that both of the daughter partons from the $W \to q\bar{q}'$ decay are contained within the jet. For jets matched to the parent W boson, at $p_{\text{T}} \sim 200$ GeV only 50% of the jets are fully

- (We are working on a simpler, more theoretically safe definition)
- The question what does the tagger do if there are additional jets in the cone, or we are in the case where most of the top is in the cone but some energy is outside, and finally if you are in a multi-top final state what does the tagger do if it has a b-jet from one top and a W from another.
- This is highly non-trivial and something we will need to think about on the experimental side...

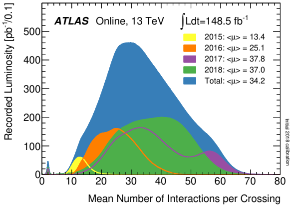
Particle Flow Jet Reconstruction

Topoclustering

- The ATLAS detector contains a huge number of calorimeter cells.
- Therefore it is desirable to only include those that contain the signals we are interested in such that we suppress the noise.
- We use an iterative process to create connected groups of cells that contain signals;
  1. Select cells with $|E| > 4\sigma$ where σ is the cell noise (including pile-up)
  2. Add all cells touching (in 3D) the selected cells with $|E| > 2\sigma$, and repeat.
  3. Add a final layer of cells with no cut is added.
- We also split large clusters that contain minima to stop these growing too big.
- These "blobs" of cells form the fundamental calorimeter objects that we build calorimeter jets from.

Pile-up

- Pile-up is the effect of other interactions to the one we are interested in.
- *In-time* pile-up are particles produced in the same bunch crossing.
- *Out-of-time* pile-up is the residual signals in the calorimeter from other bunch crossings as the calorimeter is sensitive over a longer time than the 25ns between collisions.
- The effects of pile-up is that there are many additional topoclusters in the calorimeter – this increases the measured energy of jets and also degrades the resolution – I will show these effects later and discuss how we mitigate these.
- Additionally jets that are purely pile-up are reconstructed.

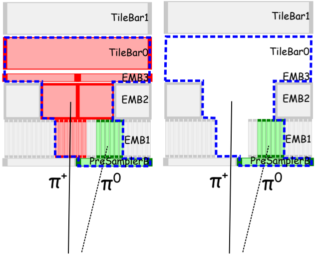


Particle Flow

- Particle flow is based on the principle that we want to take advantage of both the tracker and calorimeter.
- The tracker:
  - has better resolution at low momenta
  - can distinguish pile-up and hard-scatter particles
  - has better angular resolution
- The calorimeter:
  - has better resolution at high momenta
  - can measure neutral particles
- The principle behind the ATLAS particle flow algorithm is that we don't want to double count the signal from charged particles by having both the track measurement and calorimeter energy deposit.
- Therefore we remove the energy in the calorimeter, cell-by-cell, from those particles that we want to use the track measurement.

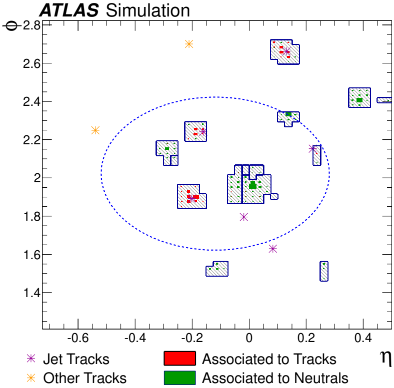
Particle Flow

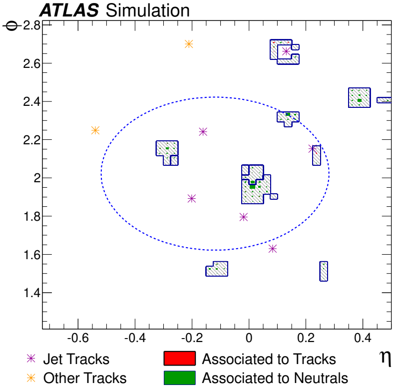
- For low momentum tracks we extrapolate them to where the particle should be in the calorimeter.
- Then the expected energy from that particle is removed - including removing the entire cluster if it is similar to the expected energy.
- Then the resulting set of tracks + remaining calorimeter clusters should represent the total energy flow of the event without double counting!
- This is done for both HS and PU tracks, but then we only form physics objects from the HS tracks – natural pile-up suppression.



Particle Flow - an example jet

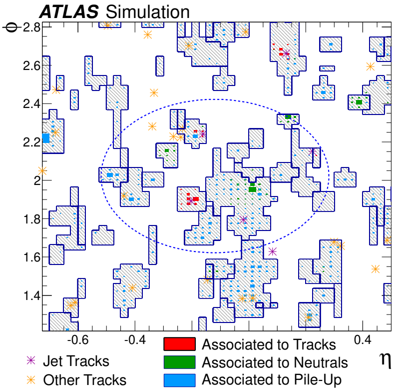
- Before (left) and after (right) the particle flow energy subtraction. (no pile-up)
- 2nd layer of the EM calorimeter.





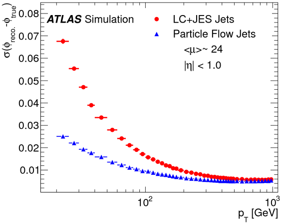
Particle Flow - an example jet

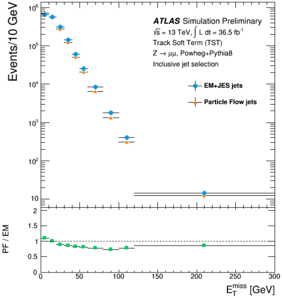
- Before (left) and after (right) the particle flow energy subtraction. ($\mu = 40$)
- 2nd layer of the EM calorimeter.

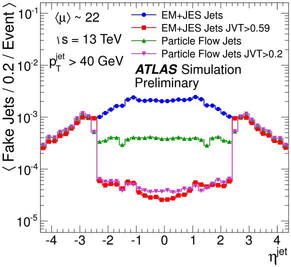


Particle Flow - the benefits, and re-interpretation

- The benefits include a distinct improvement in the jet resolution (see next section), improvement in the angular resolution of jets, reduction in the tails of missing transverse energy and a natural suppression of pile-up jets.
- The latter originates as the charged part of the pile-up jet has been removed making it less likely to have sufficient momenta to enter into an analysis selection.







Particle Flow - the benefits, and re-interpretation

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- The latter originates as the charged part of the pile-up jet has been removed making it less likely to have sufficient momenta to enter into an analysis selection.
- However, we are now assuming that we can reconstruct tracks for the particles in the jet. If a signal has O(cm) displacement then the tracks may end up looking like pile-up tracks and real jets will be removed (this also happens for the usual pile-up suppression algorithms requiring track confirmation on jets).
- It is not envisioned that such displaced analyses would use particle flow jets but re-interpreting analyses targetting prompt signal in displaced models should always be done with care...!

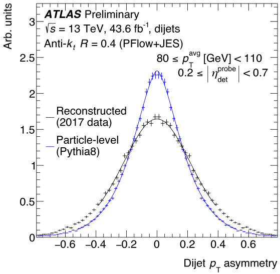
Jet Energy Resolution - measurement and understanding

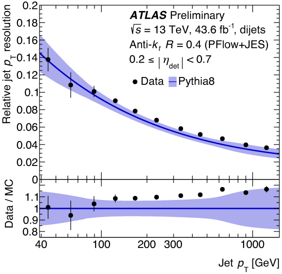
Jet Energy Resolution - measurement and understanding

- The jet energy resolution is how accurately we can measure jets.
- Improving this was one of the main motivations for the development of the particle flow algorithm.
- Careful readers of ATLAS papers through the first years of Run II will have noticed that the jet energy resolution systematic uncertainties were some of the leading experimental uncertainties – these should be much reduced in current and future publications due to the work to measure the resolution *in situ* I am about to describe.
- We use two different techniques to measure the resolution;
  1. Di-jet balance
  2. Noise term due to pile-up using random cones

Jet Energy Resolution: Di-jet balance

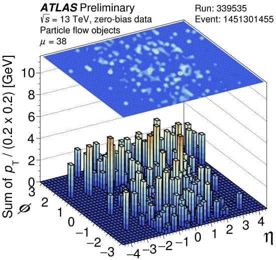
- In di-jet events we expect any imbalance to come either from radiation outside of the jets, or from resolution effects.
- In the data we measure the asymmetry; $(p_T^{\text{jet1}} - p_T^{\text{jet2}})/(p_T^{\text{jet1}} + p_T^{\text{jet2}})$.
- A deconvolution is then used to extract the gaussian resolution taking into account the imbalance expected at truth level from simulated samples.
- The extracted resolution (which is slightly worse in data then in MC) is shown below.

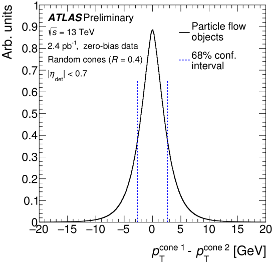


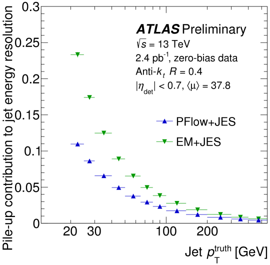


Jet Energy Resolution: Noise Term

- At low p_{T} the resolution is dominated by pile-up effects.
- To measure the fluctuations expected with in the catchment area of a jet random cones are placed in zero-bias events.
- The difference between the p_{T} of two cones give the size of the fluctuations.
- These are then scaled to the calibrated jet scale to evaluate the impact of pile-up on the resolution - the distinct advantage of PFlow can now be seen.

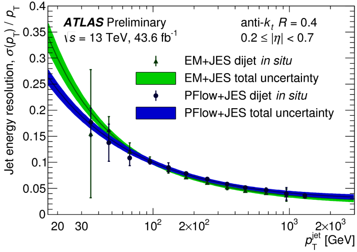


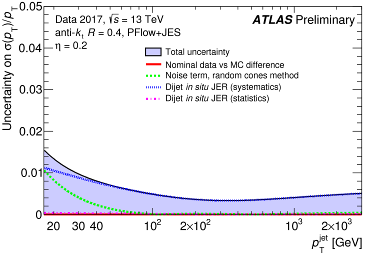




Jet Energy Resolution: Results

- A combination of the di-jet and random cone methods is performed to measure the Jet Energy Resolution across the full p_{T} range.





Conclusions

- I have shown a few of the ongoing CP developments on the JetEtmiss side that are starting to make their way into ATLAS searches.
- Each brings significant improvements to the detector performance, and in the $E_{\mathrm{T}}^{\mathrm{miss}}$ significance case has been demonstrated right through to the analysis level.
- However, these do require some care when re-interpretations are made – I believe that solutions should be possible but we probably need to provide some guidance to the outside community.
- Any questions?