Pruning and Q-Jets at ATLAS

BOOST 2013– Flagstaff, Arizona

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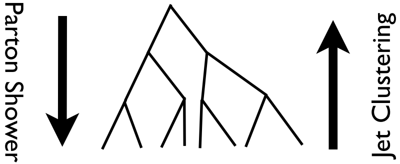
Showing results from ATLAS-CONF-2013-087

New Work in the Theory Community

- Last year at BOOST: ATLAS implements jet grooming and many "simple" jet substructure techniques
  - Simple, as in, "you can write it down in one or two lines"
  - Simple does not mean ineffective– these techniques were confirmed to be very effective at discriminating boosted objects!
- Over the past year, many developments in "more complicated" techniques in the theory community
  - Looking deeper into the parton shower, potentially using more information in our jets
- Today, showing first ATLAS results on one of these techniques– Q-Jets: {1201.1914}
  - Close collaboration with theorists has been critical for these results– many thanks for all the help!

Q-Jets: A New Approach to the Parton Shower

- Naively, people think of jet clustering as the inverse of the parton shower



- But the parton shower is actually not invertible!
- This means that many different showers could have produced the same jet
- Q-Jets asks: since there is no “right” inverse, why not study as many as we can?
  - Do not settle for just one clustering history per jet: many “inverses” are possible!

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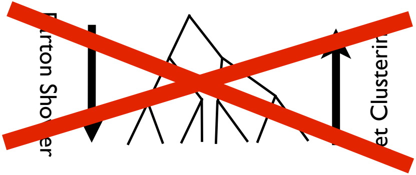

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Q-Jets: Many Interpretations of the Same Jet

- How do we get **multiple jets** out of the same jet?
    - Add a **non-deterministic element** to jet clustering: each run will produce a different outcome
- Instead of choosing the minimum distance pair when clustering jets, choose a **random pair**
    - Not completely random: weighted by the normal distance metric and α, called **rigidity**
    - Also run **jet pruning**: reject merges when pairs are wide apart, with disparate p_T
        - Much more likely to happen when choosing random pairs!
        - More details in ▸ backup
- Since every clustering will be different, **run clustering many times** and generate a distribution of Q-Jets

How to Select Pairs

- Choose a random pair *ij*, using the weights:

$$\omega_{ij}^{(\alpha)} = \exp\left\{-\alpha\frac{d_{ij} - d^{min}}{d^{min}}\right\}$$

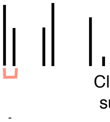
- **What do these weights mean?**
- If $d_{ij} = d^{min}$ then $\omega_{ij} = 1$
  - $\longrightarrow$ This is the largest weight: all others will be equal or smaller
  - $\longrightarrow$ The “best” pair is the most likely pair in Q-jets, and the “worst” pair is the least likely
- If $\alpha \to \infty$ then $\omega_{ij} = 1 \Leftrightarrow d_{ij} = d^{min}$, otherwise, $\omega_{ij} = 0$
  - $\longrightarrow$ If α becomes large, only the “best” pair has any weight: normal pruning occurs
- If $\alpha \to 0$ then $\omega_{ij} = 1 \ \forall\ ij$
  - $\longrightarrow$ If α becomes small, all pairs have equal weight

Quick Aside: Why Pruning?

- With Q-jets, we want **distributions of jets**: each jet should be different!
    - But if you just sum the same 4-vectors, the order doesn't matter: if you want different jets, you need to be modifying them somehow
- Pruning provides a **merge-by-merge criteria** for rejecting constituents
    - Always checking how far apart, and how unbalanced in p_T, your pairs are
- Q-jets provides "random" pairs for merging: pairs are much more likely to be rejected when they are random!
    - Which constituents get rejected will depend on the exact clustering history: **possible to get very different jets**

A Demonstration (Or Three)

- Start with three identical initial histories: **clusterings will produce different Q-Jets**!



Close pair selected:
succeeds, merges

Q-Jet 1

Far pair selected:
fails, softer discarded

Q-Jet 2

Close pair selected:
succeeds, merges

Q-Jet 3

- Each final clustering has different constituents pruned off, leading to a **different mass**

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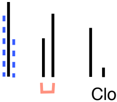

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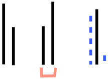

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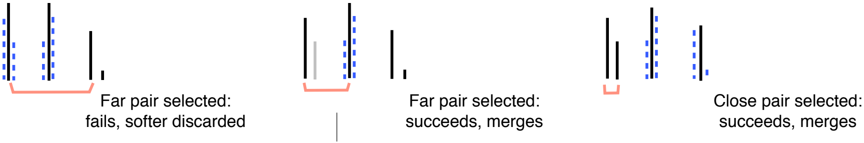

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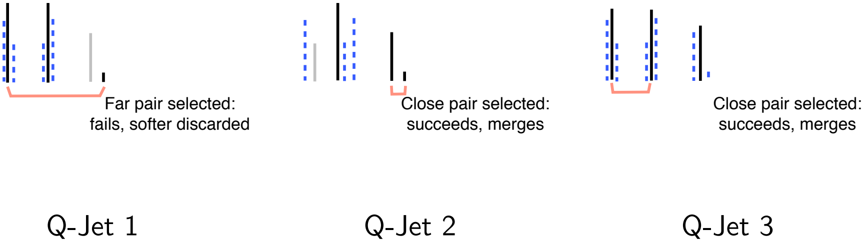

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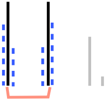
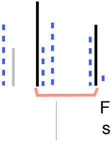


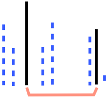
Final pair selected: succeeds, merges

Q-Jet 1



Final pair selected: succeeds, merges

Q-Jet 2



Close pair selected: succeeds, merges

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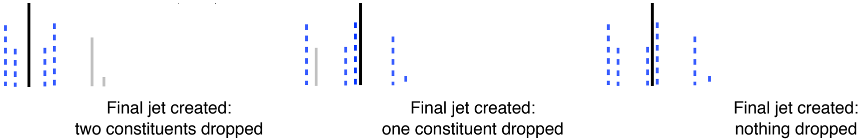


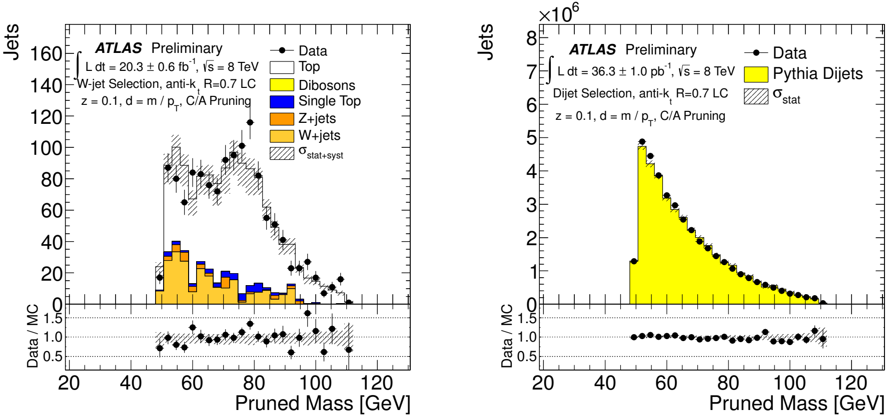
Q-Jet 1 Q-Jet 2 Q-Jet 3

- Each final clustering has different constituents pruned off, leading to a **different mass**

How to Test Q-Jets at ATLAS?

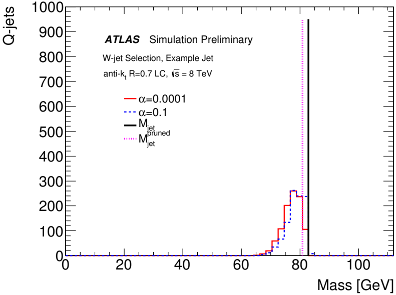
- Want to test the performance in ATLAS data: important to analyze not just in background but also **signal**
  - Have a nice, large sample of **boosted** W-**jets** from semi-leptonic top events: use these as signal!
  - QCD is the standard background we fight against: use **multijet events** for this
- Our studies will compare these two event classes, and pruned anti-k$_t$ $R = 0.7$ jets with cuts:
  1. 200 GeV $< p_T <$ 350 GeV: high enough p_T for merged W, but not high enough to merge into top-jets
  2. 50 GeV $< m <$ 110 GeV: W mass window
- NB: why $R = 0.7$? Pruning works well here!

Pruned Mass

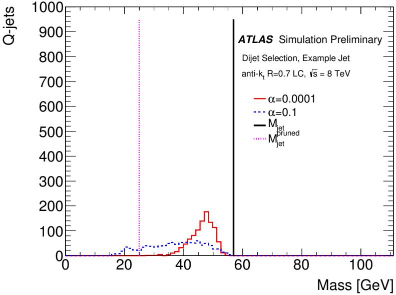


- Want to see if our sample actually has *W*-jets
  - **See a peak**, in data and MC!
- **Good data/MC agreement** in both *W*-jets and QCD, but especially good in QCD

Example Jets



W-jet



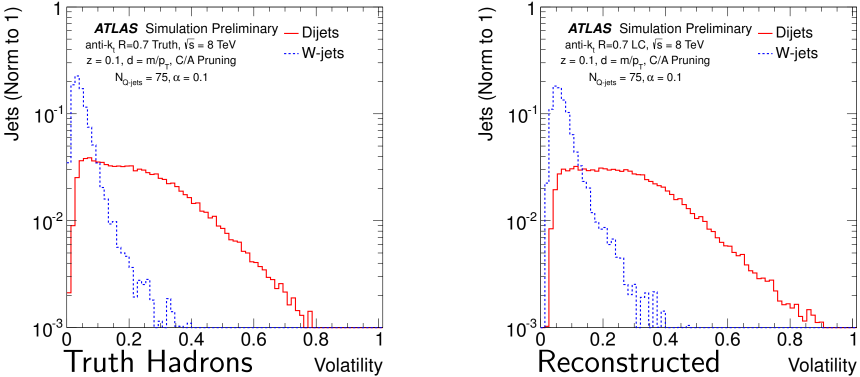
QCD-jet

- A W-jet has a **small spread** in masses for its Q-jets: a QCD jet has a **very large spread** in masses for its Q-jets

Jet Volatility

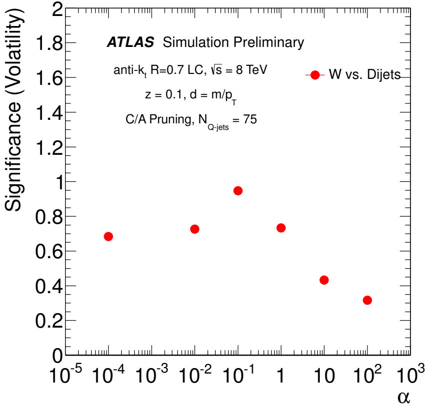
Volatility: Making an Observable from Q-Jets

- Inspired by the previous plots, define $\nu = \Gamma / \langle m \rangle$, where $\Gamma = \text{RMS}$



- Volatility, with $N_{Qjets} = 75$ and $\alpha = 0.1$, for W-jets and QCD-jets
  - Truth-jets on left, reconstructed jets on right
- See **very good discrimination** between signal and background!

Optimization vs α

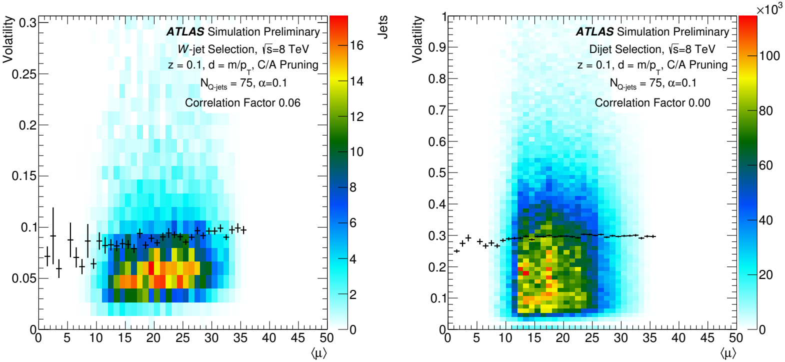


- Define significance as:

$$S = \frac{\langle QCD \rangle - \langle W \rangle}{\sqrt{\Gamma(QCD)^2 + \Gamma(W)^2}}$$

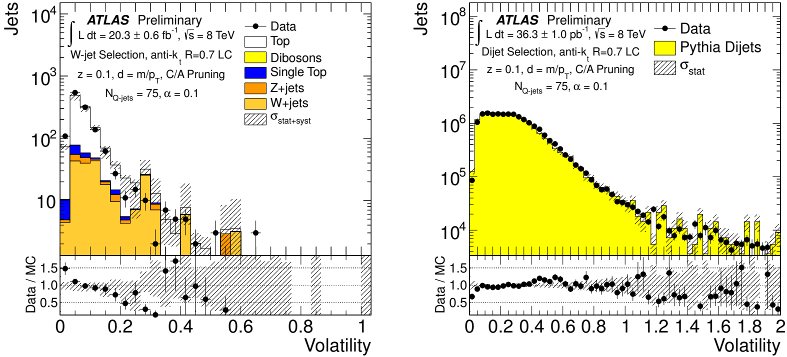
- Attempting to answer: which α gives best separation?
  - See that $\alpha = 0.1$ performs best: confirmed later in final efficiency/rejection numbers

Resistance to Pileup



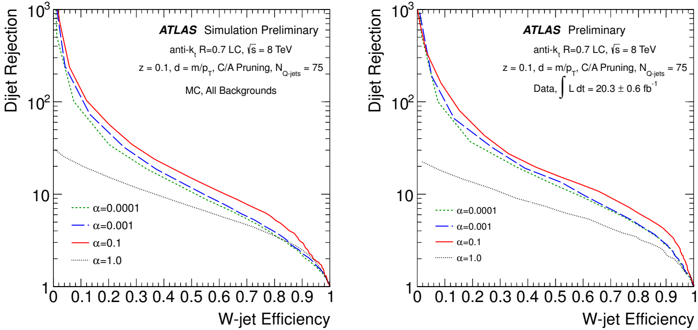
- Volatility vs μ for W-jets (on left) and QCD-jets (on right), in MC
  - **Not a strong dependence**: note that left plot has axes zoomed in

Data and MC (Volatility)



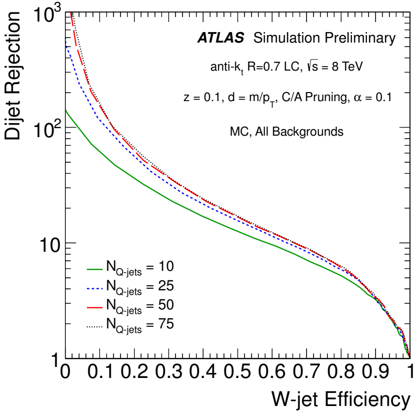
- **Generally very good agreement** seen in data/MC!
    - W-jet events have slightly worse agreement: data has lower values of volatility

Efficiency/Rejection vs α



- Signal efficiency (x-axis) and background rejection (y-axis) for MC (left) and data (right): use plots from previous slide as inputs
- **Data and MC agree very well**, as expected from previous agreement
- 15 QCD-jet rejection at 50% W-jet efficiency– **strong performance**
- $\alpha = 0.1$ has the best separation by a small amount

Efficiency/Rejection vs N_{Q-jets}



- Same plot for MC, now comparing N_{Qjets}
  - **Much shallower optimization**: all perform nearly as well as the others
  - Slight degradataion for $N_{Qjets} = 10$: $N_{Qjets} = 25$ is the lowest value where performance has plateaued

Comparing to N-subjettiness

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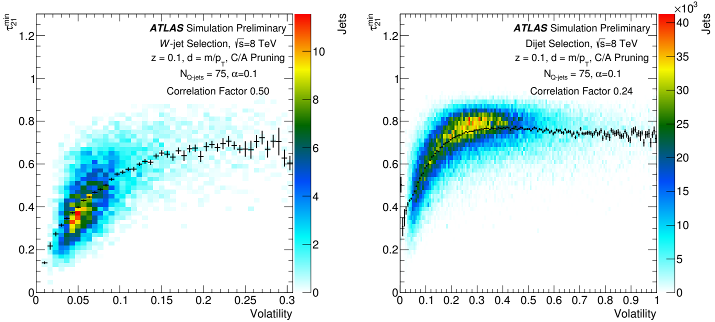
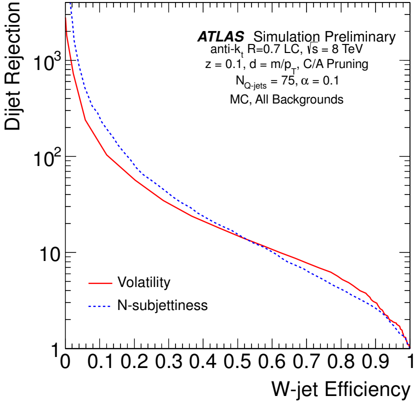


- How does volatility compare with existing W-tagging techniques, i.e. N-subjettiness?
- See some correlation, but especially in dijets, not very strong
  - Suggests a powerful potential combination of the variables
- More information on N-subjettiness in ▸ backup

Efficiency/Rejection with N-subjettiness



- Now, compare the full ROC curve for both variables
- **See generally similar performance**
  - At high efficiency, volatility is a little stronger
  - At low efficiency, N-subjettiness is a little stronger
- Next step: a combination, exploiting the strengths of each

Conclusions

Summary

- Q-jets are **a new way to interpret jets**: focus on multiple possible clustering histories, motivated by non-invertibility of parton shower
  - The first time such an idea is being considered!
- ATLAS has measured Q-Jets in **data and reconstructed MC**
  - Can obtain a factor of 15 QCD-rejection for 50% W-jet efficiency in the 200 GeV $< p_T <$ 350 GeV regime– **very competitive with existing techniques**, with a possibility for combinations to further improve performance
  - Compatible with results/expectations from theorists
  - See **good data/MC agreement**
  - Volatility shows **only slight dependence** on pileup
- Just the tip of the iceberg: volatility is the first application of Q-jets at ATLAS– looking forward to seeing more!

Thank You For Your Attention!

Backup

Q-jets: The Algorithm

- Algorithm proceeds as follows:
  1. Start with a jet found by any jet algorithm and collect the constituents into a list of constituents.
  2. Compute a set of weights ω_{ij} for all pairs of four-vectors. Define a probability $\Omega_{ij} = \omega_{ij}/N$, where $N = \sum \omega_{ij}$.

$$\omega_{ij}^{(\alpha)} = \exp\left\{-\alpha \frac{d_{ij} - d^{min}}{d^{min}}\right\} \tag{1}$$

  3. Generate a random number, using Equation 1 as a probability density function, and choose a pair from above according to the probabilities Ω_{ij}.
  4. Consider this pair for merging, and veto (as in normal pruning) if they fail the standard pruning cuts (see ▸ backup)
  5. Continue until all pairs are merged: the result is one Q-jet. The algorithm can be repeated multiple times to generate a distribution of Q-jets for every jet.

Jet Pruning

- Adapted from the theory paper:
  1. Start with a jet found by any jet algorithm, and collect the constituents into a list L. Define parameters d_{cut} and z_{cut}.
  2. Rerun a jet algorithm on the list L, checking for the following condition in each recombination $i, j \to p$:

$$z = \frac{\min(p_{Ti}, p_{Tj})}{p_{Tp}} < z_{cut} \text{ and } \Delta R_{ij} > d_{cut} \tag{2}$$

  3. If the conditions in 2) are met, do not merge the two branches 1 and 2 into p. Instead, discard the softer branch, i.e., veto on the merging. Proceed with the jet algorithm.
  4. The resulting jet is the *pruned jet*, and can be compared with the jet found in step 1.
- In practice, usually select C/A as the algorithm in step 2), and $z_{cut} = 0.1$ and $d_{cut} = m/p_T$

Jet Reconstruction

- Use both $R = 0.4$ and $R = 0.7$ jets in the analysis
  1. $R = 0.4$ LC jets are used only for event selection
     - These jets are fully calibrated (with pileup corrections, in-situ corrections)
     - Events with a jet which failes “looser” are rejected
  2. $R = 0.7$ jets are the objects of study
     - No calibration applied: none available for pruned $R = 0.7$ jets– this should be a small effect at high p_T, central η
     - $R = 0.7$ required for pruning to function: does not work with smaller/larger jets
     - Studies performed on truth particles, LCTopo clusters, and tracks

Other Objects

- *b*-tagging used for selections
    - Scale factors applied, 70% working point used
- MUID muons used for selections
    - Fully corrected, all scale factors used
    - Standard selections from top group, but use older isolation definition
        - Mini-iso from top group not avaiable in SMWZ D3PD's
- MET prescription from HSG3 used
    - Fairly standard, full jet calibrations applied, etc.

Event Selections

- Goal of the study is to analyze the performance of Q-jets in data and MC, in both signal and background
    - We want to be able to say “If I have a jet, what does Q-jets say about whether it is a W-jet?”
- Two sets of cuts are used to select signal (real W) and background events (fake W) with high purity
    1. $t\bar{t}$ selection: supplies boosted W-jets as signal sample
    2. Dijet selection: supplies light-quark and gluon jets as background sample

$t\bar{t}$ Selection

- Require standard semi-leptonic $t\bar{t}$ selection from top group:
  1. Passes GRL
  2. Passes standard quality checks
  3. Muon trigger: `EF_mu24i_tight` OR `EF_mu36_tight`
  4. 1 good muon with $p_T > 25$ GeV, no electrons
  5. 4 good jets ($p_T > 20$ GeV, JVF > 0.5, $|\eta| < 2.5$), at least 1 b-tagged at 70%
  6. MET > 20 GeV, $MET + M_T > 60$ GeV
- Plus our cuts:
  1. Lead $R = 0.7$ jet has 200 GeV $< p_T^{pruned} <$ 350 GeV
     - Enough p_T for boosted W, not enough for boosted top
  2. Lead $R = 0.7$ jet has $|\eta| < 1.8$
  3. Lead $R = 0.7$ jet has 50 GeV $< m^{pruned} <$ 110 GeV
     - Select W-jet candidates
  4. The b-tagged jet from step 5) above does not overlap with the lead $R = 0.7$ jet
     - Used to remove combinatoric backgrounds

Dijet Selection

- Dijet selection is as follows (note that we study the subleading $R = 0.7$ jet):
  1. Passes GRL
  2. Passes standard quality checks
  3. Leading $R = 0.4$ jet required to pass the `EF_j145_a4tchad` trigger treshholds ($p_T > 185$ GeV)
     - Unprescaled trigger would not give many jets in our p_T range of interest
  4. Leading $R = 0.4$ jet required to be isolated from the subleading $R = 0.7$ jet ($\Delta\phi > 2.0$) to remove trigger bias
  5. Subleading $R = 0.7$ jet has 200 GeV $< p_T^{pruned} <$ 350 GeV
  6. Subleading $R = 0.7$ jet has $|\eta| < 1.8$
  7. Subleading $R = 0.7$ jet has 50 GeV $< m^{pruned} <$ 110 GeV

More Details on N-subjettiness

- Adapted from the original paper:
  - τ_N is the normalized sum over p_T weighted distances to the closest of N subjets:

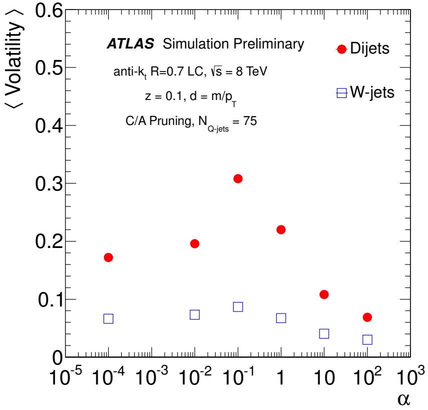
$$\tau_N = \frac{1}{R \sum_k p_T^k} \sum_k p_T^k \min_J \{\Delta R(k, J)\} \tag{3}$$

  where the k-index counts over jet constituents, J-index counts over subjet axes, R is the jet radius. Subjet axes are determined by minimizing τ_N over possible candidate axes

- τ_{MN} is defined simply as:

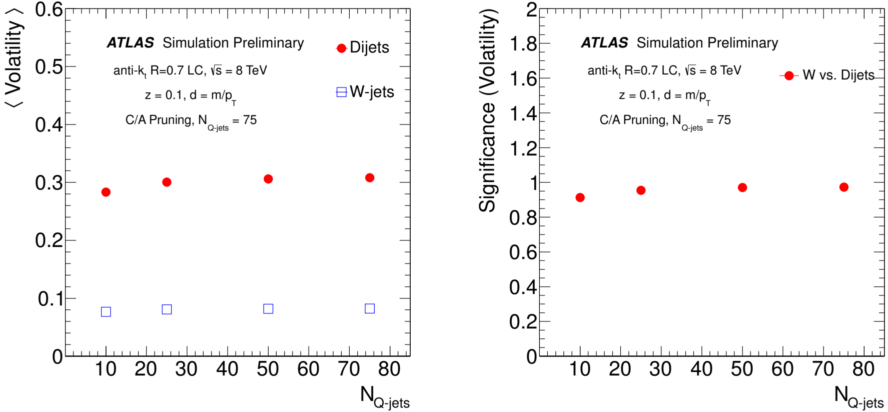
$$\tau_{MN} = \frac{\tau_M}{\tau_N} \tag{4}$$

Optimization vs α



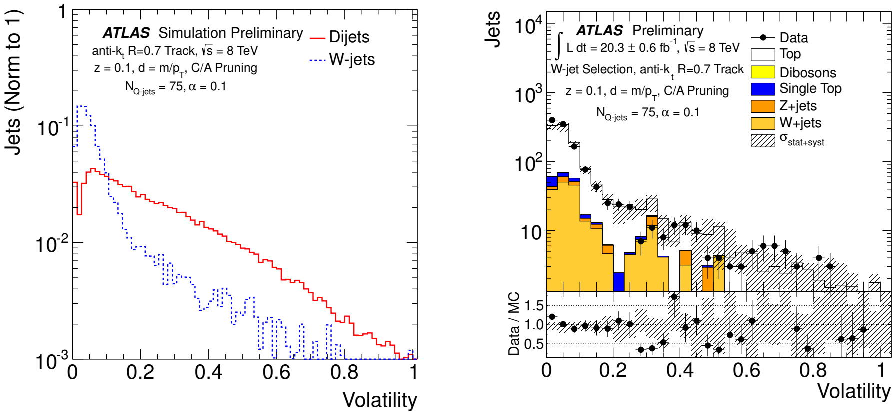
- Here, show mean volatility in both dijet and W-jets
- See again that $\alpha = 0.1$ has the best separation

Optimization vs N_{Q-jets}



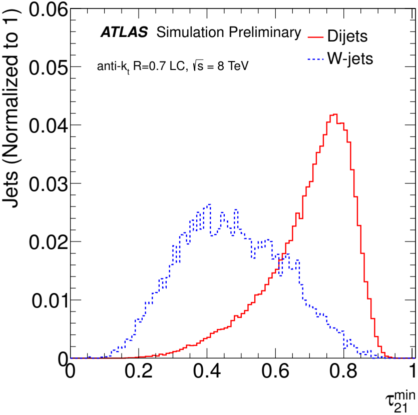
- Here, show mean volatility in both dijet and *W*-jets, but as a function of N_{Q-jets}
- **Not much difference!** Can use as low as 25?

Track-Jet Result



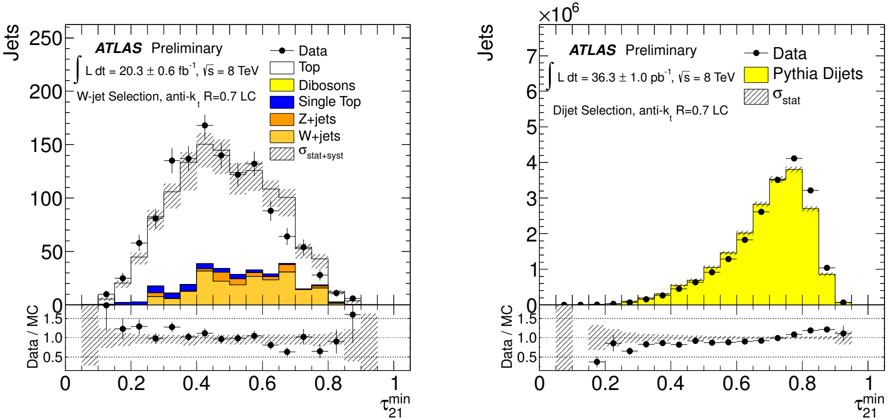
- Can also calculate Q-jets with **only charged particles**: track-jets matched to calorimeter jets
- See good discrimination, but **much less**
- Data/MC agreement is very similar to full calorimeter results

N-Subjettiness: Discrimination



- Always calculate N-subjettiness with **unpruned constituents**
  - Following the result that has given best discrimination for trimming as well
- Using **minimized** N-subjettiness here (first ATLAS result on this)
  - Use one-pass minimized k_T axes for calculation
- Good discriminaton visible between W-jets and dijets here

N-Subjettiness: Data/MC Agreement



- for the anti-k$_T$ $R = 0.7$ jets shown here
  - NB: using **unpruned** constituents: similar to what we do with trimming
- **Generally good agreement**, in signal and background

Systematics for *W*-jets

- Following sources are included in systematics:
  1. $t\bar{t}$ cross-section
  2. Luminosity
  3. $R = 0.4$ JES/JER
  4. $R = 0.7$ JMS (conservative 7% shift), no JES
  5. *b*-tagging uncertainties
- Additionally, *MET* softterm, muon scale factors, and muon trigger systematics were found to be negligible