Report from the BOOST 2011 Working Group

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June 15, 2011

The Report

A majority of the attendees to the BOOST 2011 Workshop (link) on jets, jet substructure, and exotic jets (e.g. lepton jets) engaged in an *in depth discussion* on the goals of this community.

Self-imposed mandate

- Outline the physics goals aimed at by this community.
  - Define the ***"Why?"*** of this subfield.
  - Identify the most important objectives with the hope that this will guide both theoretical and experimental progress.
- Establish an inventory of observables to answer the ***"Why?"***
  - Which observables can we measure?
  - Which measurements will most effectively answer the most pressing questions?
  - How easy are these measurements to perform?

None of this would be possible without the forum of experts – both theoretical and experimental – fostered by the BOOST 2011 Workshop series.

Why are we studying jet substructure?

Find new physics

- Characterize observables relevant to new physics searches:
  - figures of merit for improvement over conventional techniques
  - ability to combine with others; establish correlations
- Establish influence of experimental uncertainties:
  - Magnitude of detector (in)efficiency and acceptance
  - How to "unfold" for these effects

Test old physics.

- Demonstrate / improve understanding of pQCD at the energy frontier:
  - Validate theory error estimates
  - Perform comparisons to precise QCD (NLO) calculations
- Measure or mitigate other old friends and foes:
  - Underlying event and pile-up
  - Measure color reconnections

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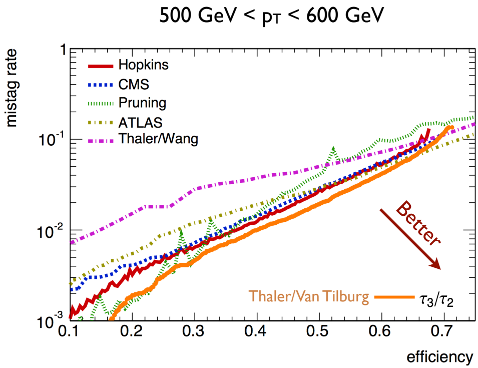
Example: characterization of observables

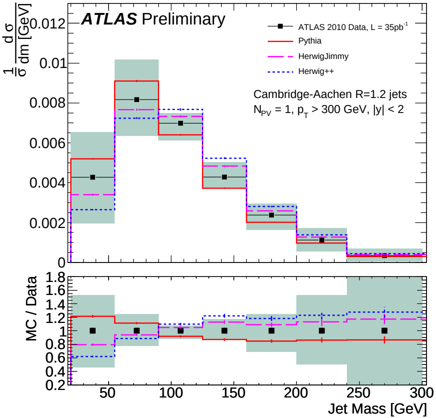
One of the primary deliverables from BOOST 2010 was a set of benchmark data sets with which to characterize substructure observables related to top-tagging. Only a narrow sliver of the phase space of observables and measures of their impact in SM and BSM searches.



What are the most important observables?

Example: measuring, correcting for detector effects

ATLAS results use a bin-by-bin unfolding to correct for various detector effects. The jet mass spectrum is a good example for which the unfolding corrections seem to have a large uncertainty.



Is this the best approach?

How will we achieve our physics goals?

Define measurability and calculability.

- Establish real data samples in which to test new observables
  - $W/Z/\gamma$+jet, dijet, multijet
- Quantify influence of experimental and theoretical uncertainties:
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  - Existence of theoretical calculations

Establish a priority list of measurements and calculations.

- **Jet mass:** correlations, systematics, physics sample
- **Properties of groomed jets:** grooming procedure, Δ w.r.t. un-groomed
- **Jet shapes:** width, subjet/track multiplicities, angularities, Ψ
- Others to keep in mind:
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Generally accepted that jet mass is one of the most important observables to understand both theoretically and experimentally.

Priority measurements of the jet mass.

- **2D mass vs. p_T**
- **2D mass vs. mass in di-jet events**
- **2D mass vs. ΔR to the nearest jet in multi-jet events**

Other important aspects and measurements.

- Methodology
  - Theoretical calculations require a precise topology
  - Hard cuts on third (second) jets in di-jet ($W/Z/\gamma$+jet) events
  - Jet input constituent dependencies (tracks/clusters/towers/truth)
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Jet grooming

Jet grooming requires both strong experimental verification as well as proven theoretical tractability.

Priorities: theoretical side.

- Are all grooming procedures well-behaved in NLO calculations?
- Which ones are "the best"? (requires figures of merit)
- Can these procedures be applied to all jets?

Priorities: experimental side.

- Measurements of jet observables **before and after grooming**:
  - Jet mass
  - N-subjettiness
  - Charged track / subjet multiplities
- Aspects of grooming itself
  - "Extent" (e.g. Δp_T, Δm^{jet}) of grooming as a function of pile-up, underlying event
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- Can these procedures be applied to all jets?

Priorities: experimental side.

- Measurements of jet observables **before and after grooming**:
  - Jet mass
  - N-subjettiness
  - Charged track / subjet multiplities
- Aspects of grooming itself
  - "Extent" (e.g. Δp_T, Δm^{jet}) of grooming as a function of pile-up, underlying event
  - Experimental tractability

Jet grooming

Jet grooming requires both strong experimental verification as well as proven theoretical tractability.

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Jet shapes

Jet shapes have a more established history and they continue to shed light on jet substructure. Shapes in addition to the traditional "Ellis shapes" (whoever that is) have been deemed a high priority.

Priority measurements.

- **Jet width (a.k.a. girth, broadening):** quark vs. gluon discrimination, direct correlation to jet mass
- **Multiplicities:** subjet, track, constituent multiplicities (also provides some quark vs. gluon discrimination)
- ***N*-subjettiness:** more refined concept of subjet multiplicity with proven usefullness

Additional considerations.

- **Angularities:** ΔR_{iJ}^{2-a} where $a \to 1 \equiv$ jet width/girth/broadening
- Most helpful to obtain fill distributions (Ψ is a wonderful example of how the published data are given in terms of statistical averages in p_{T} or ΔR bins)
- How does the use of different constituents change the observed values of the jet shapes? Does this indicate limitations in resolution/granularity?

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Summary and conclusions of the BOOST 2011 WG

A lot of progress made in the last few years!! But....we still have lots to do.

Priorities

- Measure **2D distributions of jet mass** vs. a few other important observables.
- Identify the **efficacy, applicability, tractability (experimental and theoretical) and usability** of the jet grooming procedures.
- Add some **non-traditional jet shape** observables to the mix.
- Make sure that **theoretical predictions** exist for the above listed priority measurements.

Conclusions

- Much of this well underway in the experiments, *but we need to get better / more efficient at making these results public!* Because...
- Close collaboration with theorists is obviously important; we have already discovered that some measurements that we thought were more useful are not (e.g. m_{jet1} vs. m_{jet2}).

Additional Material

N-subjettiness, τ_N

Measures the extent to which a given jet is likely to be composed of N subjets by first identifying a set of subjets and then comparing the energy flow in the jet to the direction of these subjets [1].

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min \{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\} \tag{1}$$

$$d_0 = \sum_k p_{T,k} R \tag{2}$$

The sum runs over the k constituent particles in a given jet where $p_{T,k}$ are their transverse momenta, and $\Delta R_{j1,k} = \sqrt{\delta y_{j1,k}^2 + \delta \phi_{j1,k}^2}$ is the distance in $\Delta y \times \Delta \phi$ between a candidate subjet $j1$ and a constituent particle k.

→Uses ratios of momenta and exclusive subjets

→Sensitive to subjet multiplicity, not so much kinematics

Dipolarity, $\mathcal{D}$

$\mathcal{D}$ is intended to measure the color "connectedness" of the final state and once again uses the concept of subjets in order to define reference points within a jet. For a jet, J, with two subjets, $j1$ and $j2$, located at (η_{j1}, ϕ_{j1}) and (η_{j2}, ϕ_{j2}) the distribution of jet constituents i around the line segment $\ell_{j1,j2}$ connecting the two subjets defines $\mathcal{D}$ [2].

$$\mathcal{D} \equiv \frac{1}{R^2_{j1,j2}} \sum_{i \in J} \frac{p_{Ti}}{p_{T_J}} R_i^2, \tag{3}$$

where $R^2_{j1,j2} \equiv (\eta_{j1} - \eta_{j2})^2 + (\phi_{j1} - \phi_{j2})^2$.
This definition may also be extended beyond the study performed in Ref. [2] in the case of three-body decays where three subjets are measured by defining $\mathcal{D}$ with respect the third subjet as well: $\mathcal{D}_{12}$, $\mathcal{D}_{23}$, $\mathcal{D}_{13}$.

→Uses ratios of momenta and exclusive subjets
→Sensitive to subjet topology, in particular the direction

J. Thaler and K. Van Tilburg.
Identifying Boosted Objects with N-subjettiness.
page 26, November 2010.

A. Hook, M. Jankowiak, and J. G. Wacker.
Jet Dipolarity: Top Tagging with Color Flow.
page 7, February 2011.