Jet Substructure: Measurable vs Calculable Working Group Report

Matthew Schwartz, Iain Stewart, Jesse Thaler, Jon Walsh and others

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1 Introduction

This working group considered how jet substructure should be studied experimentally. An attempt was made to characterize the priorities of early measurements at the LHC. Priority motivations for measuring jet substructure were

- Characterizing observables relevant to new physics searches
- Understanding sensitivity to detector effects and how to unfold them
- Compare to precision QCD calculations and validate theory error esimates

A number of observables were considered and prioritized in light of the above motivations. The top priorities were

- Jet mass
- Groomed jets
- Jet shapes

Below we give more details of these three categories.

2 Jet mass

Jet mass was generally agreed upon to be the single most important jet substructure observable to measure. It is directly relevant to many new physics searches, for example resonance searches in boosted top [Sal; refs] and the

Higgs search in association with a W/Z and high p_T [Jon B.; refs] which are already underway. It is an observable which is sensitive to underlying event and pileup and therefore can be used to characterize these effects in data and test Monte Carolo simulations. Finally, it is something which in certain circumstances can be calculated theoretically to high accuracy.

A number of high priority jet mass measurements were discussed. From the theoretical point of view, priorities are

- **Mass in $\gamma/W/Z$ + jet events.** These events are clearer than dijet events both experimentally and theoretically.
  - Differential mass distribution of the jet, for different $p_T's$: 50,100,200,300,400 GeV
  - For theory purposes it would be helpful to have the mass in for the exclusive $\gamma/W/Z$ + jet cross section, where there is a hard veto on additional jets, such as $p_T^2 < 10\% p_T^\gamma$. This sample is also useful experimentally for jet energy calibrations
- **Mass in dijet events**. These events are more complicated theoretically, but have higher cross section so produce higher p_T jets and higher statistics samples
  - Doubly differential distribution in the two jet masses
    - Projections such as the heavier jet mass or sum of the jet masses are particularly interesting theoretically
    - The correlation between the two masses is interesting. There is already unexplained behavior of this observable in CDF data [Pekka; refs]. For example, $R = \frac{AD}{BC}$, where A, B, C, D are the number of events in 4 quadrants separated by, say $m < 50$ GeV
  - The leading and subleading (in p_T) sample is not so interesting theoretically, but may be useful experimentally.
  - For theory purposes it would be helpful to have the sum of jet masses in events with a hard cut on the 3rd hardest jet, ie. the exclusive dijet cross-section.
- **Mass in multijet events**
  - In events with 3 jets, with a hard P_T cut (say ¿200 GeV) on 2 (or 3) of the jets, it would be useful to look at how the jet mass of the hardest jet depends on the distance ΔR to the next hardest jet.

Additional data on

- mass dependence on H_T,# pileup events, rapidity
- difference in mass from using charged tracks, towers, clusters
- jet algorithm parameters, such as the jet size R or algorithm

would also be very interesting

3 Groomed Jets

An important tool for many new physics searches is jet grooming. There are three grooming algorithms on the market: pruning, filtering and trimming. Filtering and pruning are currently being studied by both ATLAS and CMS. Trimming should be studied too.

It is important to measure

- Measure **both** the groomed **and** ungroomed mass
- Compare the effect of grooming as a function of pileup.
- Try to test grooming as dependent on underlying event, through a measure of the amount of underlying event [Gavin; ref]

Besides jet mass, it would be good to see the effect of grooming on

- Jet broadening
- N-subjettiness
- using charged tracks only

Experimentalists need input from the theorists on which grooming algorithms would be useful to measure, and for what signals/channels. Are any grooming algorithms useful to measure on jets outside of jet substructure (for general use)? Are there any important theoretical considerations for the calculability/feasibility of the grooming algorithms? What grooming methods can reasonably be measured in the coming year by each collaboration?

- Which algorithms work best?
- What is the best way to determine which algorithms work best?
- Which algorithms are calculable?

4 Jet shapes

Jet shapes give us an understanding of the radiation pattern within a jet. Jet mass is a simple jet shape, discussed above. In addition, high priority jet shapes to measure are

- Girth/Jet broadening/Width/1-subjettiness. There are a number of versions of these, but we want to make sure a standard definition is used. The observables is

$$g = \frac{1}{p_T^{\rm jet}} \sum_i (\Delta R)_i P_T^i, \quad \Delta R_i = \sqrt{(y_i - y_{\rm jet})^2 + (\phi_i - \phi_{\rm jet})^2} \tag{1}$$

  Here it is important that the rapidity (rather than pseudorapidity η) be used for the jet. The rapidity should be based on the jet being a *massive* 4-vector. [Jason; refs]

- The jet girth vs jet mass 2D distribution would be interesting as well

- 1-subjettiness (equivalently jet angularities) with several choices for the angular measure exponent β $(= 2 - a)$. Note that mass $(\beta = 2)$ and broadening/girth $(\beta = 1)$ are special cases of 1-subjettiness.

- 2-subjettiness (or > 2). Priority is for the angular measure exponent $\beta = 1$ (jet broadening measure), since this is expected to be less sensitive to underlying event/pileup. Second priority is $\beta = 2$ (thrust measure).

- Multiplicities (subjet or track). Most substructure studies (such as Quark vs Glue [jason; refs)benefit from having as fine resolution as possible

  - Subjet multiplicity, from reclusting with a small r.
    - How small can you take r?
    - How low can you take the energy cutoff on jet constituents
  - Charged track multiplicity. What is the resolution

Other jet shapes which may be of interest as well are

- Jet angularities

- planar flow

5 Global event shapes

Finally, let us mention that global hadronic event shapes are also of interest. These event shapes can be measured with jets, but should also be measured with particles. In particular

- 1-jettiness $\mathcal{T}_1$ in $\gamma/W/Z$ + jet events. 1-jettiness acts as a jet-veto to give a 1-jet exclusive sample. It is given by three components one for the jet and one for radiation aligned with each beam, $\mathcal{T}_1 = \mathcal{T}_1^{\mathrm{jet1}} + \mathcal{T}_1^a + \mathcal{T}_1^b$. The measurement of $\mathcal{T}_1^{\mathrm{jet1}}$ gives a measurement of the mass of the exclusive jet, while $\mathcal{T}_1$ is the sum of jet and beam-radiation masses. [Iain; refs]

- 0-jettiness aka beam thrust. This would be very useful for studying the underlying event, and tuning the implementation of underlying event in Monte Carlo. It may also be useful for understanding theory uncertainties for jet vetoes which are relevant for the Higgs search [Iain; refs]

- Y_{23}, transverse thrust [Gavin; refs] It is important to measure more than one of these event shapes because they have different sensitivities to perturbative corrections and underlying event. Theoretically they probe the color mixing anomalous dimensions. They can also help us understand why alpgen+showering (LO/PS matching) does worse than original monte carlo (PS alone) in some comparisons to data.