Substructure Based Observables for Finding New Physics

Jeremy Love
Outline (Disclaimer)

- This talk focuses on current use cases of jet substructure at the LHC and a brief look at the challenges they face
  - Apologies in advance for my biases
  - Current uses
  - Looking towards 14 TeV
  - Questions for discussion

- Please see Nhan's talk for a specific example
Jet Substructure: (This) Experimentalist's Definition

- Referring to showers from massive particles contained in a single reconstructed jet
- Consider all non-four vector quantities of a jet which do not treat the shower as a single object
  - Jet mass, number of subjets, splitting scale, n-subjettiness, etc...
- As hadronically decaying massive particles go to higher $p_T$, their decay products become more collimated from the boost
The Utility of Substructure Observables

- ATLAS and CMS so far have used jet substructure in two ways for BSM searches
  - Use in SM measurements is just beginning
    - Ex: differential cross section measurements of W and top-quark

Case 1: Jet Tagging
- Use substructure to tag Standard Model particles to identify a desired final state
  - Sub-category 1:
    - Top Quark
  - Sub-category 2:
    - SM Bosons W,Z,H
    - Nhan's talk
- Typically complimentary to lepton final states

Case 2: Anomalous Distributions
- Analyze substructure variables for new physics
  - Ex: Bump hunt Jet Mass distribution
- Unique search not necessarily otherwise possible
  - Require better understanding of substructure variables
The Case for Substructure Tagging

- Goal is to reject QCD background events and tag hadronic decays of massive particles
  - Efficiency turn on with \( p_T \) as decay products begin to overlap
  - Limit when overlap is too large to distinguish

- Confounding factors
  - Pile-up interactions contribute to showers and effect observables
  - There is \( p_T \) dependence of substructure variables ATLAS-CONF-2012-150
    - Inherent and unavoidable in some cases

- Ex. Diboson resonance search ZZ/ZW
  - \( Z \rightarrow \mu\mu \ Z/W \rightarrow jj \)
  - Two channels
    - Resolved: 2 distinct jets
    - Boosted: 1 large-R jet with JetMass consistent with an EW Boson
A wide variety of substructure based tagging techniques are available and being used:

- HEPTopTagger
- Q-Jets
- Mass-Drop Filtering
- Shower Deconstruction
- Jet Mass
- n-Subjettiness
- Splitting Scale
- Number of \( k_T \) subjets
- Permutations there of and more..

Great variations in complexity yield comparable performance:

- Ex: HEPTopTagger 40% with 40x rejection
  - (Black points)
- Optimized cut based tagger 40% with 30x rejection
  - (Black line)
The Future of Substructure Tagging

- Can we get to b-Tagging-like efficiencies and rejections?
  - Typically \( \sim 70\% \) efficiency with 100x rejection

- Can we gain by event based instead of object based tagging?
  - Ex: Bjorken-Plumbing
  - Algorithm for mapping radiation field in the parton frame
Mitigation of Pile-up Effects

- For the 8 TeV LHC run the $<\mu>$ was 20 per bunch crossing
  - Two primary mitigation techniques were adopted
- Trimming reconstructs subjets and removes energy associated with subjets which contribute less than some fraction of the total jet $p_T$
  - Favored by ATLAS
- Pruning is similar to trimming but additionally removes large angle radiation
  - Favored by CMS

Figures from JHEP09 (2013) 076
Moving to $O(14)$ TeV

- Energy and jet $p_T$ increases
  - Many substructure observables correlated with $p_T$
    - JetMass, $n$-subjettiness, splitting scale...
  - New phenomenon turn on such as W-strahlung
    - Backgrounds change
    - Are these included in simulation?
  - Tagging becomes more difficult
    - Many tagger efficiencies “roll over” around 1.5-2 TeV

- Pile-up increases
  - Well proven techniques to mitigate this at 7-8 TeV
    - Do they still work at $\langle \mu \rangle \approx 40?\ 50?\ 80?$

- Physical limitations of our detectors imply that substructure feature size below $\sim 0.1$ are not measurable
Work for substructure at High-$p_T$

- High-$p_T$ top tagging studied as part of the Snowmass effort
  - Results agree with current ATLAS and CMS results
- Work is already ongoing to improve taggers as well
  - Ex: Original HEPTopTagger was $p_T$ dependent
    - Great improvements have been achieved

arXiv:1307.6908

Prompt Questions for Discussion

- Tagging:
  - Many taggers have similar performance, is this a sign more information is needed?
  - Can our current taggers be re-optimized for high-$p_T$?
  - Are there fundamental limits to the $p_T$ scale at which these techniques work?
  - Would variable radius jet reconstruction improve tagger rejection?

- Looking for anomalies:
  - So far Jet Mass has been used.
  - What measurements are needed to help constrain substructure modeling at higher $p_T$?
  - New effects lurking around the corner?
    - W-strahlung?

- Pile-up mitigation:
  - Do pruning and trimming perform stably at higher $<\mu>$?
  - Are smaller area jets a better way to minimize the impact of PU?
  - Investigating other techniques? Mass-drop filtering etc...
Additional Material