Substructure Based Observables for Finding New Physics

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Outline (Disclaimer)

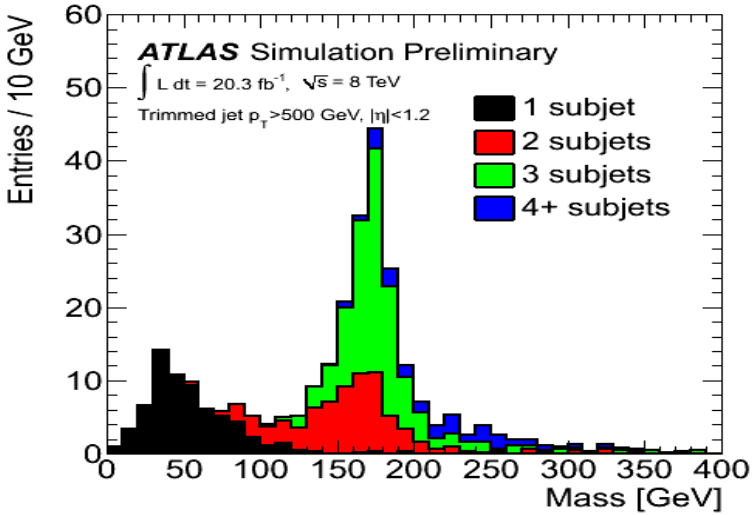
- This talk focuses on current use cases of jet substructure at the LHC and a brief look at the challenges they face
    - Apologies in advance for my biases
  - Current uses
  - Looking towards 14 TeV
  - Questions for discussion

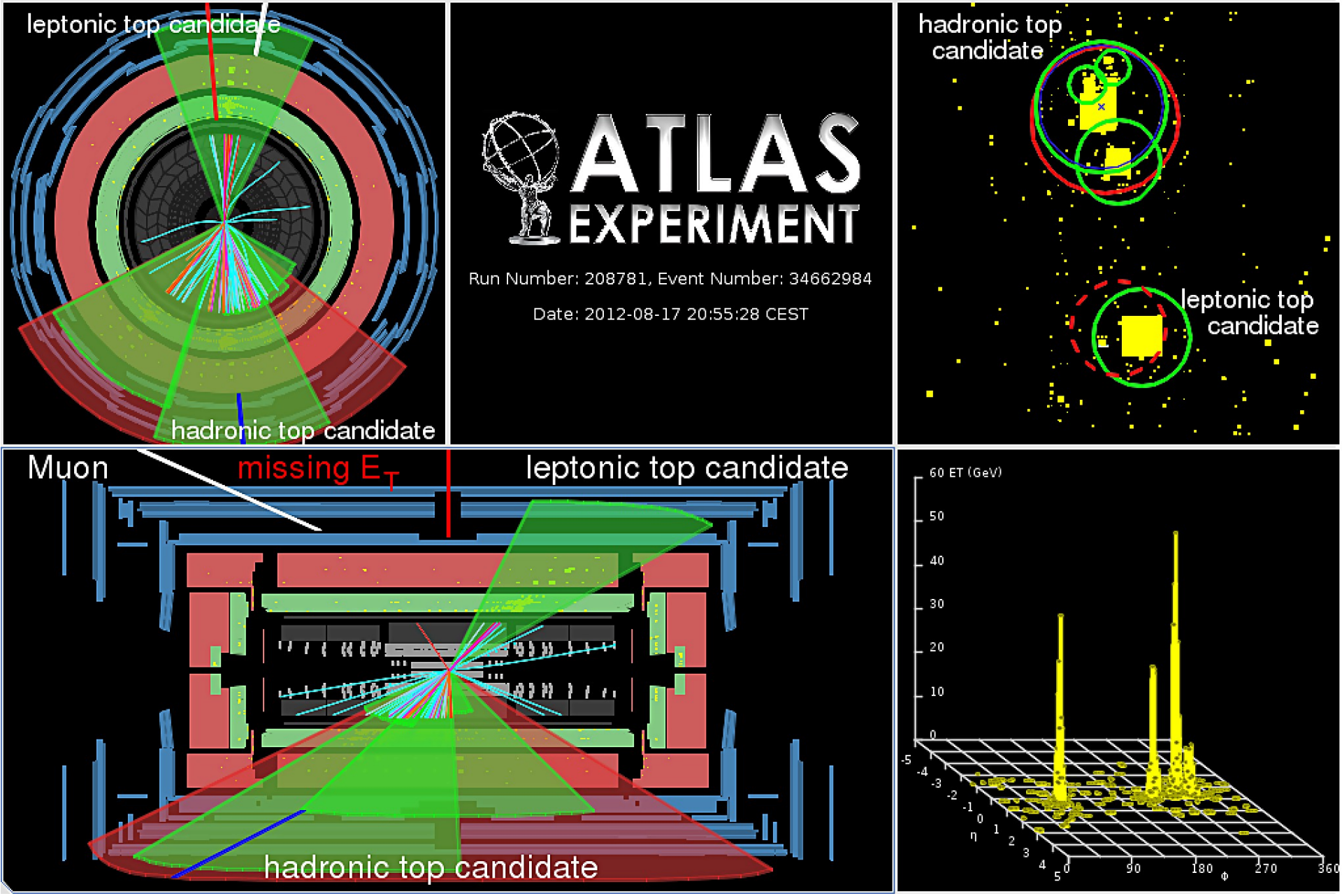
- Please see Nhan's talk for a specific example

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




leptonic top candidate
hadronic top candidate
ATLAS
EXPERIMENT
Run Number: 208781, Event Number: 34662984
Date: 2012-08-17 20:55:28 CEST
hadronic top candidate
leptonic top candidate
Muon
missing E_T
leptonic top candidate
hadronic top candidate
60 ET (GeV)
50
40
30
20
10
0
-5
-4
-3
-2
-1
0
1
2
3
4
5
η
0
90
180
270
360
Φ

The Utility of Substructure Observables

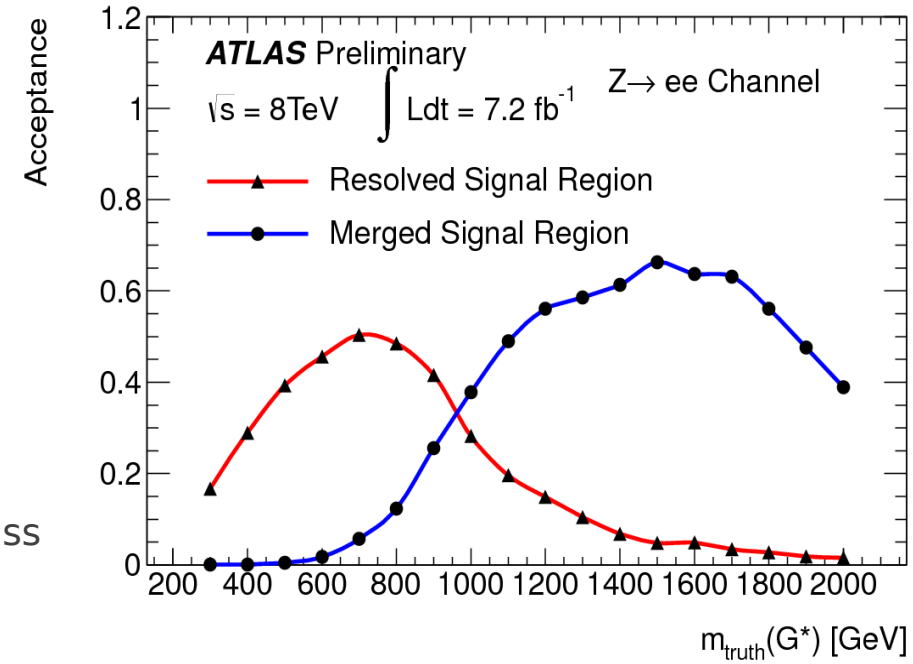
- ATLAS and CMS so far have used jet substructure in two ways for BSM searches
  - Use in SM measurements is just beginning
    - Ex: differential cross section measurements of W and top-quark

- 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
  - Efficency 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

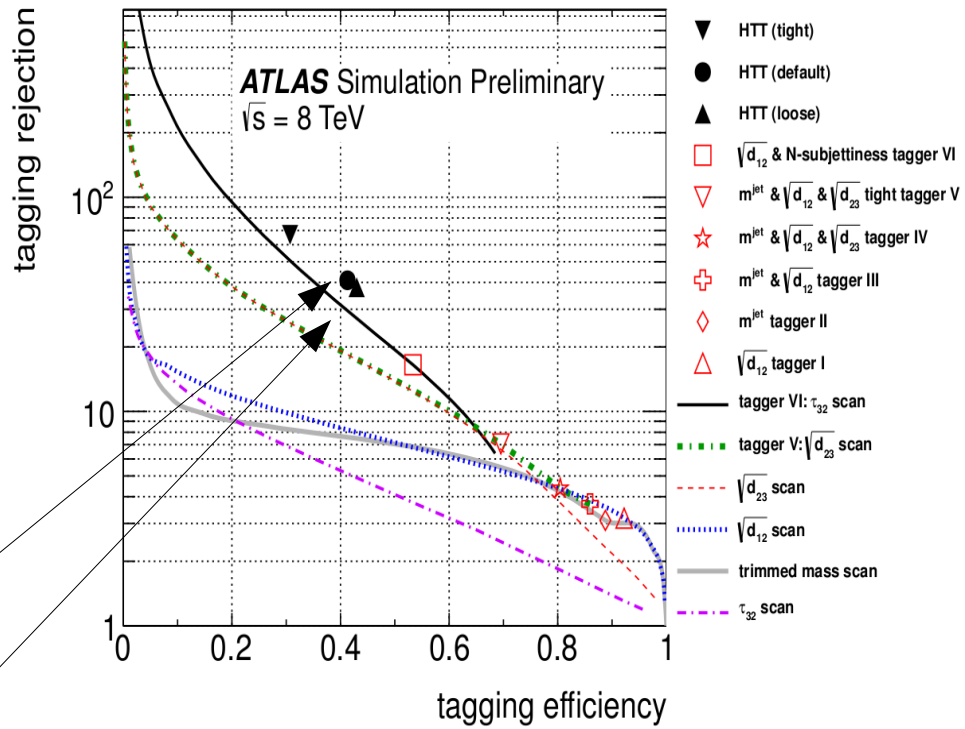


- Ex. Diboson resonance search ZZ/ZW
  - Z->μμ Z/W->jj
  - Two channels
    - Resolved: 2 distinct jets
    - Boosted: 1 large-R jet with JetMass consistent with an EW Boson

A Survey of Substructure Based Top Tagging

- A wide variety of substructure based tagging techniques are available and being used
  - Just a few:
    - 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)

ATLAS-CONF-2013-084



The Future of Substructure Tagging

- Can we get to b-Tagging-like efficiencies and rejections?
  - Typically ~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
    - Phys.Rev. D45 (1992) 4077-4087

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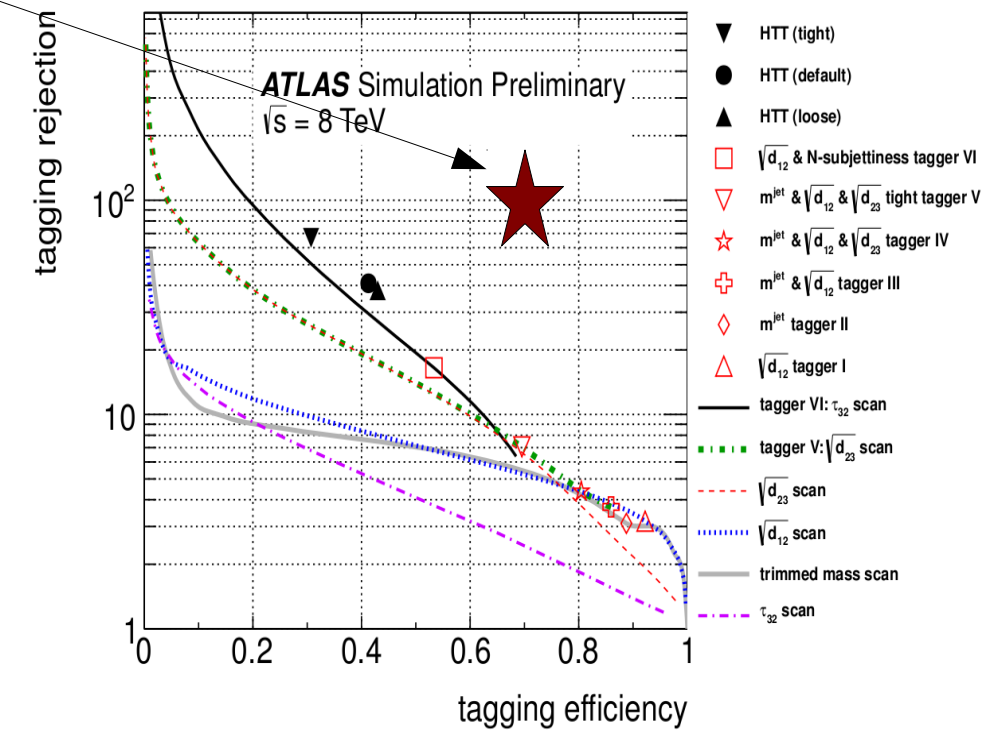
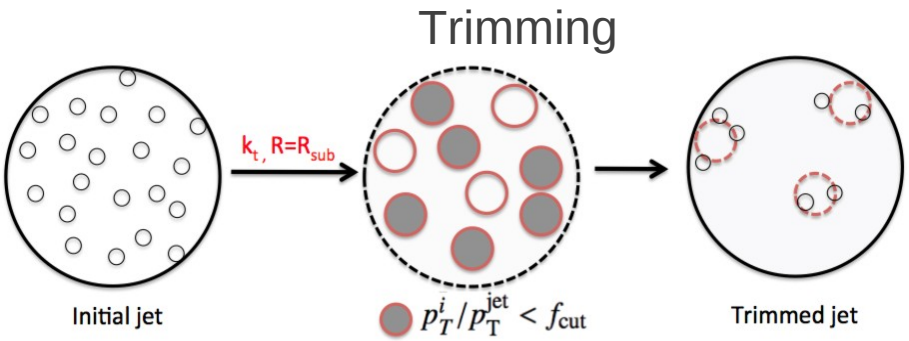
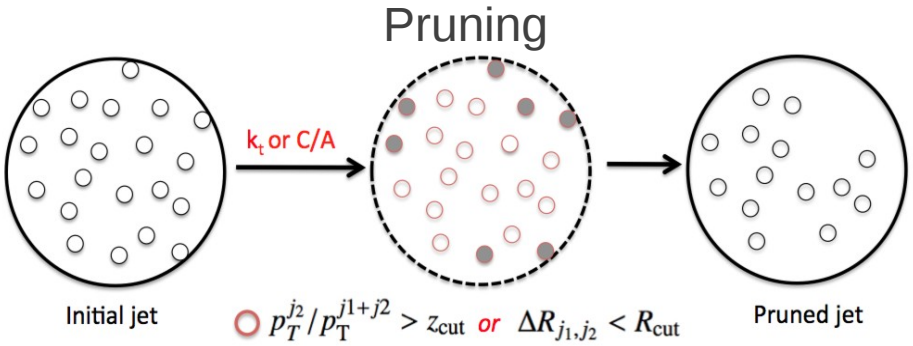


Mitigation of Pile-up Effects



JHEP 1002:084 (2010)



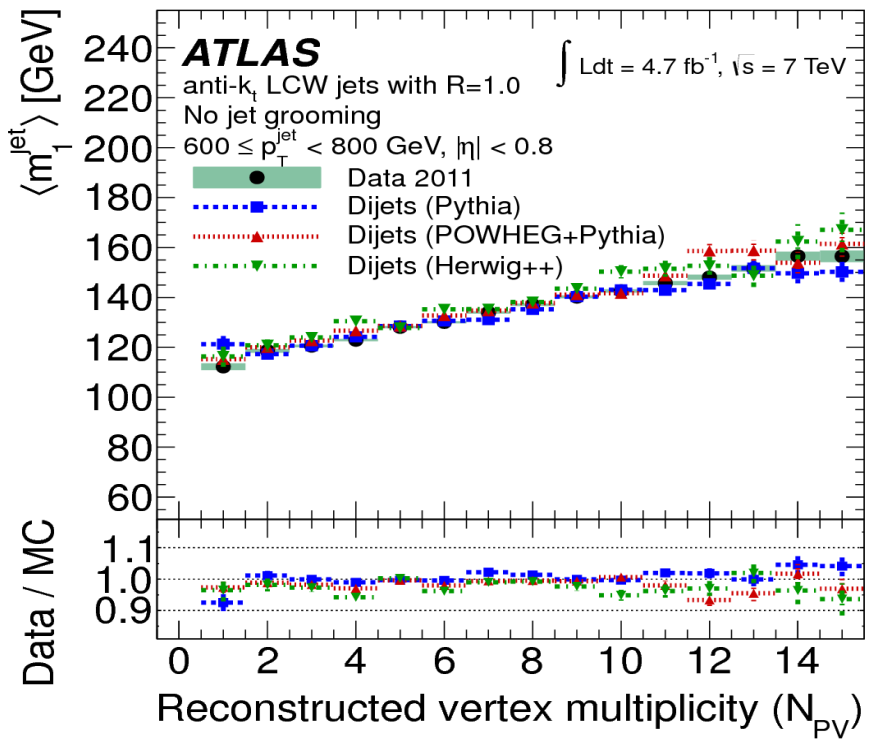
Phys Rev D. 80, 051501 (2009)

- For the 8 TeV LHC run the <μ> 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 subtructure 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 <μ> ≃ 40? 50? 80?

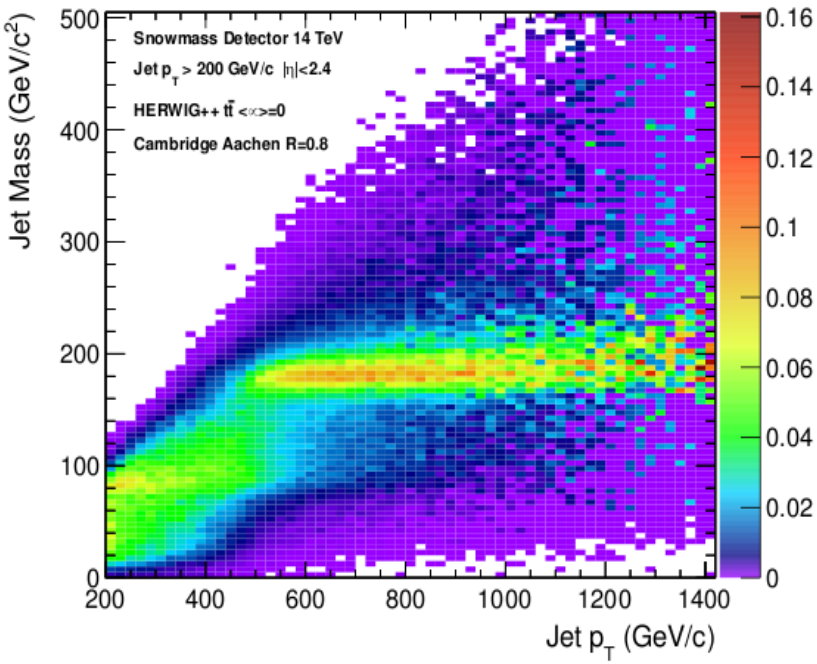


JHEP09 (2013) 076

- Physical limitations of our detectors imply that substructure feature size below ~0.1 are not measurable

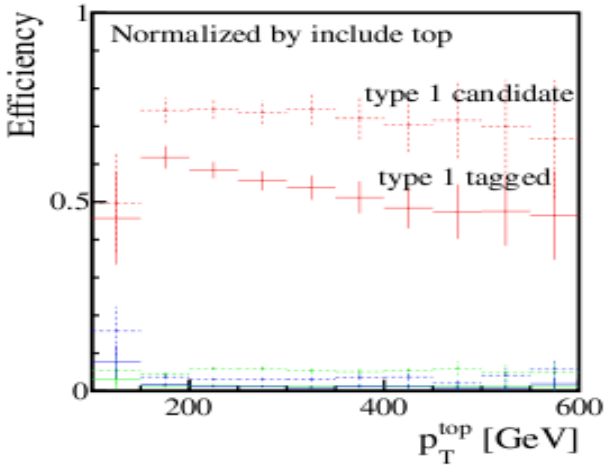
$$R \approx \frac{2m}{p_T}$$

Work for substructure at High-p_T



arXiv:1307.6908

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



Phys. Rev. D.85: 034029(2012)

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