Jet Substructure Measurements at ATLAS

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On behalf of ATLAS collaboration

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Jet Substructure
Jet Substructure
A large radius jet of $R = 2m/p_T$ can contain all decay products

Hadronically decaying top quark, Higgs/W/Z bosons, new heavy particles ...

Exploit the internal structure of the large radius jet coming from signal to distinguish them from large radius jet coming from background (light quark, gluon, lepton)

Preferred jet algorithms are $k_t$ or CA, as they preserve clustering order, but anti-$k_t$ is used to construct the large-radius jet
I'M NOT FAT

I'M JUST BIG CONED
Why Jet Substructure

Searches for New Physics

- Deviation from SM predictions in Higgs coupling
- New heavy bosons
- Top partners/vector like quarks
- ...

Substructure techniques help!
Reduces combinatorics in busy final states.
**Why Jet Substructure**

**Searches for New Physics**

- Deviation from SM predictions in Higgs coupling

New boson-hbosons:

- Most new developments to design (tagging) algorithms to discriminate signal (fat) jets from light quark/gluon background jet

VLQ

W’

Substructure techniques help! Reduces combinatorics in busy final states.
Why Measurement?

Bulk properties of large-radius jets depend on pQCD modelling.

Non negligible differences from data are observed in MC predictions.

Soft-drop is insensitive to non-global logarithmic terms, leading to precision analytic calculation of substructure variables.

\[ \langle n_{\text{charged}} \rangle \]

\[ \text{ATLAS} \]

\[ \sqrt{s} = 8 \text{ TeV} \]

\[ L_{\text{int}} = 20.3 \]

\[ p_{T}^{\text{miss}} > 0.5 \text{ GeV} \]

\[ \begin{array}{c}
\text{Quark Jets (Data)} \\
\text{Gluon Jets (Data)} \\
\text{Quark Jets (Pythia 8 AU2)} \\
\text{Gluon Jets (Pythia 8 AU2)} \\
\text{Quark Jets N^3LO pQCD} \\
\text{Gluon Jets N^3LO pQCD}
\end{array} \]

\[ \text{Jet } p_{T} \text{ [GeV]} \]

\[ \text{Eur. Phys. J. C76(6), 1-23 (2016)} \]
Why Measurement?

Jet (sub)structure is mostly dependent on Parton Shower models

Non negligible differences from data are observed in MC predictions

(Unfortunately) Grooming to get rid of uncorrelated radiation also throws away the soft part we wish to tune to!

"Your garbage is my treasure"

Attributed to Stefan Prestel
Why Measurement?

Sensitive to both perturbative and non-perturbative QCD ("precision substructure")

Input to tune/improvement models and analytic calculations

Helps in tagging algorithm development.
Soft Drop

Start with a jet $j$ and it is split into last two subjets

If:

$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{cut} \left( \frac{\Delta R_{12}}{R_0} \right)^\beta$$

Then $j$ is the final soft drop jet.

Otherwise the higher $p_T$ subjet is taken as $j$ and iterated ...

Advantage: can be compared directly to analytic calculations, factorises non-perturbative effects
Soft-dropped Jet Mass

Ratio of the soft-drop mass to the ungroomed jet transverse momentum

Collinear emission region

Resummation region

Higher beta (smaller fraction of soft energy removed)

arXiv:1711.08341
Soft-dropped Jet Mass

Ratio of the soft-drop mass to the ungroomed jet transverse momentum

Largest difference between MC and analytic calculation in NP region

NLO+NLL+NP better at low log $p$

Good agreement at resummation region for both MC and calculations
Leading experimental uncertainty from calorimeter cell-cluster energy, resolution, efficiency etc.

Cluster energy scale and resolution uncertainties estimated by track to cluster E/p ratio, angular resolution uncertainty by relative position shift

Reconstruction efficiency from unmatched tracks to clusters
\[ \sqrt{d_{ij}} = \min(p_{Ti}, p_{Tj}) \times \Delta R_{ij} \]

When combining two subjets with \( k_t \) algorithm:

- More inclusive
- Using charged particles in Z-boson events

Small values: soft splitting, Larger values: hard splitting
**k_t Splitting Scale**

When combining two subjets with $k_t$ algorithm:

$$\sqrt{d_{ij}} = \min(p_{Ti}, p_{Tj}) \times \Delta R_{ij}$$

Using charged particles in Z-boson events

**ATLAS**

$\sqrt{s} = 8 \text{ TeV}, 20.2 \text{ fb}^{-1}$

$Z \to e^+e^-, R = 1.0$

**JHEP 08 (2017) 026**

Large discrepancy at soft/collinear regime

Sherpa better than Powheg+Pythia8 at high tails
Colour Flow in TTbar Events

Colour flow modelling in MC generators is poorly constrained by current measurements

Weighted angular moments derived from jet constituents

\[ \mathcal{P}(j) = \sum_{i \in \delta} \frac{\Delta r_i}{p_T^j} \Delta r_i \]
Results

Using charged particles in semi-leptonic $t\bar{t}$ events

Close to zero for colour connected jets, uniform if no colour connection
Results

Using charged particles in semi-leptonic $t\bar{t}$bar events

**ATLAS**

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

- Data
- Statistical Unc.
- Total Unc.
- Powheg+Pythia8
- Powheg+Pythia6
- MG5_aMC+Pythia8
- Powheg+Herwig7
- Sherpa

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**Colours singlet W**

No CR between $b\bar{b}$

MCs predict stronger colour connection than data
Powheg+Herwig$^7$ describes the data the best
Looking Forward

- Jet substructure studies are essential for finding new physics in post-Higgs era in (HL) LHC and ILC.

- Need measurements, and best possible MC modelling

- Proper estimation of uncertainties, and robustness against pileup is critical