New Observables for Jet Substructure

Multi-particle Dynamics at High-p_T

Jesse Thaler

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What is Jet Substructure?

Maximizing the Physics Potential of Hadronic Final States

Upcoming Talks: Amazing Experimental Progress

[see talks by Bose, Wardrope, Loch, Marchesini, Stoebe, Matera, De Lorenzi, ...]
Multi-particle Dynamics at High-$p_T$?

Traditionally:
Jet $\rightarrow$ proxy for short-distance parton

Ordinary Jet $\rightarrow$ u/d/s/g
Tagged Jet $\rightarrow$ b, maybe c

Jet Substructure:
Use multi-hadron observables for clues about underlying physics

Angularities, Jet charge $\rightarrow$ quark vs. gluon
N-prong substructure $\rightarrow$ boosted W/Z/Top/Higgs

(and accept that jets are fundamentally ambiguous, messy)

Dependence on Jet Definition
Perturbative Fractal Structure (i.e. Parton Shower [see talk by Nagy])
Non-perturbative Hadronization Effects
Jet Contamination from UE/ISR, Pileup [see talk by Sullivan]
New Observables for Jet Substructure

N-subjettiness

with Ken Van Tilburg: 1011.2268 & 1108.2701

Energy Correlation Functions

with Andrew Larkoski & Gavin Salam: 1305.0007

(Jets Without Jets)

with Daniele Bertolini & Tucker Chan: forthcoming

Only small sampling of jet substructure tools/techniques

[see also talks by Roy, Krohn]
N-subjettiness

[JDT, Van Tilburg: 1011.2268 & 1108.2701]
Classic Jet Substructure

High mass di-top resonances

$$\sqrt{s} \gg m_{\text{top}}$$

$$\Delta R \sim \frac{2m_{\text{top}}}{p_T}$$

Heavy resonance to boosted tops...looks like QCD dijets

Robust/Growing Set of Tagging Tools:
Mass Drop, Trim/Filter/Prune, Y-splitter, Planar Flow, JHU/CMS Top Tagger, HEPTopTagger, Top Template Method, N-subjettiness, Q-Jets, Telescoping Jets, Shower Deconstruction, ...
Jet Substructure by Eye

*Coloring by exclusive $k_T$*

Boosted Top Jet, $R = 0.8$

Boosted QCD Jet, $R = 0.8$

**Boosted Top Quark**

QCD Jet ($m_{jet} \approx m_{top}$)

$$\langle m^2_{jet} \rangle \approx \alpha_s p^2_{Tjet} R^2$$

Additional discrimination possible beyond just jet mass
N-subjettiness

Testing $N$-prong substructure

\[ \tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min \{ \Delta R_{k,1}, \Delta R_{k,2}, \ldots, \Delta R_{k,N} \} \]

Find axes by minimizing $\tau_N$

Freedom to Exploit

- $\beta$

$\# \text{ subjects: } \leq N$

$\tau_N: 0$

$\# \text{ subjects: } > N$

$\tau_N: 1$

N-jettiness: [Stewart, Tackmann, Waalewijn]
N-subjettiness: [JDT, Van Tilburg]
**N-subjettiness**

*Testing N-prong substructure*

\[
\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min \{\Delta R_{k,1}, \Delta R_{k,2}, \ldots, \Delta R_{k,N}\}
\]

Find axes by minimizing \(\tau_N\)

# subjects: \(\leq N\) > \(N\)

\(\tau_N: 0\)

\(T_3/T_2: \text{Tops}\)

\(T_2/T_1: \text{W/Z/H}\)

Freedom to Exploit

N-jettiness: [Stewart, Tackmann, Waalewijn]

N-subjettiness: [JDT, Van Tilburg]
Applications in Higgs Physics

High Mass $h \rightarrow WW$

$$h \rightarrow \begin{cases} W \rightarrow q\bar{q}' \\ (boosted) \\ W \rightarrow \ell\nu \end{cases}$$

Validated on quasi-boosted semi-leptonic top sample

$R = 0.8$

[Uses pruned jet mass: Ellis, Vermilion, Walsh]

[CMS PAS HIG-13-008]
Energy Correlation Functions

[Larkoski, Salam, JDT: 1305.0007]
Quark/Gluon Discrimination

The White Whale of Jet Substructure

[see e.g. Gallicchio, Schwartz]

Jets, simplified:

Gluon Haze Surrounding...

...Eikonal Hard Quark/Gluon

In soft & collinear limit:

\[ P = \frac{2\alpha_s C}{\pi} \frac{dz}{z} \frac{d\theta}{\theta} \]

Color Factor:
\[ C_F = 4/3 \text{ (quarks)} \text{ vs. } C_A = 3 \text{ (gluons)} \]

In this limit, for most any* observable:

**Quark Efficiency** = \( x \)

**Gluon Mistag** = \( x^{9/4} \)

White Whale: Exploit subleading structure, evade Casimir scaling

Improves S/B but marginal change in significance \( (S/\sqrt{B}) \)
1-subjettiness for Quark vs. Gluon?

*a.k.a. angularities*  [Berger, Kucs, Sterman]

\[ \tau_1 = \frac{1}{p_{T,\text{jet}}} \sum_k p_{T,k} \Delta R_{k,1} \]

**Soft Emission**
- Sensitive to pattern of soft radiation
- Dominates for \( \beta > 1 \)
- Effective for quark vs. gluon

**Jet Axis**
- Hard jet core
- \( z = \) energy fraction
- \( \theta = \) splitting angle

**'Direct' contribution**

**'Recoil' contribution**
- Sensitive to displacement of jet axis
- Dominates for \( \beta < 1 \)
- Less effective for quark vs. gluon

Alternative: use recoil-free axis, e.g. “broadening axis”  [Larkoski, Neill, JDT, forthcoming]
Energy Correlation Functions

Axis-free (and recoil-free) probe for substructure

[see Banfi, Salam, Zanderighi; Jankowiak, Larkoski]

\[ \text{ECF}(1, \beta) = \sum_{i} p_{Ti} \]

\[ \text{ECF}(2, \beta) = \sum_{i<j} p_{Ti} p_{Tj} (R_{ij})^\beta \]

\[ \text{ECF}(3, \beta) = \sum_{i<j<k} p_{Ti} p_{Tj} p_{Tk} (R_{ij} R_{jk} R_{ki})^\beta \]

\[ \text{ECF}(N, \beta) = \sum_{\text{sets of } N} (N \text{ energies}) \times \left( \binom{N}{2} \text{ angles} \right)^\beta \]

Convenient Dimensionless Ratio:

\[ C_N^{(\beta)} = \frac{\text{ECF}(N + 1, \beta) \text{ ECF}(N - 1, \beta)}{\text{ECF}(N, \beta)^2} \]

\[ N \text{ narrow prongs: } C_N \rightarrow 0 \]
C₁ for Quarks vs. Gluons

\[ C₁(\beta) = \frac{1}{(p_{T\text{jet}})^2} \sum_{i<j} p_{Ti} p_{Tj} (R_{ij})^\beta \Rightarrow z \theta^\beta \]

No recoil!

NLL Resummation

Quark vs. Gluon (NLL+LO)

\[ p_T = 400 \text{ GeV}, R_0 = 0.6 \]

- \( C₁(\beta = 0.2) \)
- \( C₁(\beta = 0.5) \)
- \( C₁(\beta = 1.0) \)
- \( C₁(\beta = 2.0) \)

Better

Small \( \beta \) emphasizes higher-order quark/gluon differences

z = energy fraction
\( \theta \) = splitting angle

soft emission ➔ hard jet core

\( p_T \in [400,500] \text{ GeV}, R_0 = 0.6 \)

Quarks
Gluons

quark-like ↔ gluon-like

\begin{align*}
C₁(\beta) &= \frac{1}{(p_{T\text{jet}})^2} \sum_{i<j} p_{Ti} p_{Tj} (R_{ij})^\beta \\
&\Rightarrow z \theta^\beta
\end{align*}
Opportunity for Monte Carlo Calibration?

Pythia 8 vs. Herwig++

Parton shower:
Formally accurate to LL

$\beta$-dependence:
Starts at NLL

Determine correct behavior from data?

$$C_1^{(\beta)} = \frac{1}{(pT_{\text{jet}})^2} \sum_{i<j} pT_i pT_j (R_{ij})^\beta$$
Looking to the Future

This Talk: Observables calculable in perturbative QCD

- e.g. Infrared/Collinear Safe or “Sudakov Safe”
  [see Larkoski, JDT]

⇒ Essentially multi-parton dynamics

ISMD 2014: Fundamentally non-perturbative observables?

- e.g. $p_T^D$ from CMS
- Jet Charge
- Track-based Observables

⇒ Interplay of multi-hadron/parton dynamics

Still (some) perturbative control!
[see Krohn, Lin, Schwartz, Waalewijn; Chang, Procura, JDT, Waalewijn]
(Jets Without Jets)

[Bertolini, Chan, JDT: forthcoming]
This talk so far ✪
Jet Substructure

What lives here?

Algorithms

Subjet Finding

Jet Shapes

✩ This talk so far ✩

Jets

Closed-Form Observables

Jet Algorithms

Event Shapes
Jet-like Event Shapes
or subjet-like jet shapes

\[ \tilde{N}_{\text{jet}} = \sum_{i \in \text{event}} \frac{p_{T_i}}{p_{T_i,R}} \Theta(p_{T_i,R} > p_{Tcut}) \]

Jet Algorithm
Jet-like Event Shape

\[ p_{T_i,R} = \sum_{j \in \text{event}} p_{T_j} \Theta(R_{ij} < R) \]

Dijets @ LHC8, R = 0.6, p_{Tcut} = 25 GeV
A Hammer in Search of a Nail
Reproducing standard jet observables

\[ H_T = \sum p_T \]

\( p_T \) of hardest jet
(without identifying that jet)

Jet Trimming
[Krohn, JDT, Wang]

Dijets @ LHC8, \( R = 0.6 \), \( p_{T\text{cut}} = 25 \) GeV

Boost2010 Top Sample
\( R = 1, p_T > 200 \) GeV, \( R_{\text{sub}} = 0.2, f_{\text{cut}} = 0.05 \)

Improved triggering? Pileup mitigation? Overlapping jets?
Smoother interpolation of jet (sub)structure? Calculational tractability?
New Observables for Jet Substructure

N-subjettiness

*Effective test for N-prong substructure*

Energy Correlation Functions

*Importance of recoil-free observables for quarks vs. gluons*

(Jets Without Jets)

*Characterize (sub)jet-like structure without jet finding*

Bottom Line: Can define observables sensitive to desired physics

Interplay: Measurable ↔ Useful ↔ Calculable
Backup Slides
Boosted Regime is Inevitable

Di-tops in the standard model

<table>
<thead>
<tr>
<th>Expected number of events</th>
<th>Tevatron run II 10 at 1.96 TeV</th>
<th>LHC 2012 20 at 8 TeV</th>
<th>LHC design 300 at 13 TeV</th>
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</thead>
<tbody>
<tr>
<td>Inclusive ( t\bar{t} ) production</td>
<td>( 6 \times 10^4 )</td>
<td>( 4 \times 10^6 )</td>
<td>( 2 \times 10^8 )</td>
</tr>
<tr>
<td>Boosted production</td>
<td>23</td>
<td>( 6 \times 10^4 )</td>
<td>( 5.2 \times 10^6 )</td>
</tr>
<tr>
<td>Highly boosted</td>
<td>0</td>
<td>500</td>
<td>( 1.1 \times 10^5 )</td>
</tr>
</tbody>
</table>

[h/t Marcel Vos; Boost 2012 Report (forthcoming)]

Semi-leptonic \( t\bar{t} \): Not so extreme at 13/14 TeV

[CMS PAS B2G-12-006]
Validating 2-subjettiness

Calculations & Measurements

\[ W \rightarrow q\bar{q}^' \]

Color singlet resonance at N^3LL for \( \beta = 2 \)

[Fiege, Schwartz, Stewart, JDT]

\( W \rightarrow q\bar{q} \)

Measure in dijets at low pileup

Good agreement with parton showers