Recent theory developments on jet substructure

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"event built from jets" $\Rightarrow$ "jet built from constituents"

"cluster the event into jets"
$\Rightarrow$ "cluster jet into subjets"

- tagging
- trimming
- soft-drop
  - + recursive
  - + dynamical
  - includes modified mass-drop
- collinear-drop
- ...

"observables from jets"
$\Rightarrow$ "observables from constituents"

- jet mass
- angularities
- energy correlation functions
- jet pull
- Lund plane
- ...

* disclaimer: this is a non-exhaustive and biased list of examples
Overview

"event built from jets" → "jet built from constituents"

"cluster the event into jets"
→ "cluster jet into subjets"

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"observables from jets"
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representation of single emission phase space
→ at LL uniform ⇒ predicted deviations
uses:

1. forward: resummed calculations / parton shower building
e.g. [Gustafson ’92] [Hamilton, Medves, Salam, Scyboz, Soyez ’20]

2. backwards: map cluster steps of final jets to Lund plane
⇒ physics insights to build optimal observables

Example: Higgs tagging [Khosa, Marzani ’21]

Similarly:
- quark-gluon jets [Dreyer, Soyez, Takacs ’21]
- b-jets [Fedkevych, Khosa, Marzani, Sforza ’22]
Observables II: Jet Angularities

study family of observables

\[ \lambda_{\alpha}^{\kappa} = \sum_{i \in J} \left( \frac{p_{T,i}}{p_{T,J}} \right)^\kappa \left( \frac{\Delta R_i}{R} \right)^\alpha \]

here: calculations need IRC safety, so \( \kappa = 1 \)

parameter \( \alpha \) ⇒ probe different kinematic regimes

stayed in different frameworks

[Ellis, Vermilion, Walsh, Hornig, Lee ’10] [Hornig, Makris, Mehen ’16]

[Kang, Lee, Ringer ’18] [DR, Caletti, Fedkevych, Marzani, Schumann, Soyez → see later]

reuse energy-correlations @ NLL [Larkoski, Salam, Thaler ’13] [Larkoski, Neill, Thaler ’14] [Banfi, Salam, Zanderighi ’04]

context:

[Les Houches 15/17/19]

[Larkoski, Thaler, Waalewijn ’14]

quark-gluon tagging

\[ Z_\ell @ 13 \text{ TeV from Caletti, Fedkevych, Marzani, DR, Schumann, Soyez, Theeuwes ’20} \]
Soft-Drop: Intro

[Larkoski, Marzani, Soyez, Thaler ’14]

**idea:** remove soft wide-angle contamination

**method:** decluster w/ C/A, remove softer branch if

$$\min(\rho_{T,i},\rho_{T,j}) < Z_{\text{cut}} (\frac{\Delta R}{R})^\beta$$

**analytical understanding:** [Larkoski, Marzani, Thaler ’15]

$\rho_T$ fraction $z_g$, separation $\theta_g = R_g/R$ of splitting

\[ \Rightarrow \] using concept of Sudakov safety

calculations available at NLL, NLL’ [Kang, Lee, Liu, Neill, Ringer ’19]

[Cal, Lee, Ringer, Waalewijn ’21]
Soft Drop: Application

[CMS '18] [ATLAS '17]

procedure:
1. soft-drop groom jet constituents
2. calc standard observable "after grooming"

example: jet mass after grooming

side note: also applicable to global event shapes
[Baron, Marzani, Theeuwes '18], [Marzani, DR, Schumann, Soyez, Theeuwes '19],
even in pp [Baron, DR, Schumann, Schwanemann, Theeuwes '20]
Automated calculations
(in the SHERPA framework)

Basic soft gluon resummation

▷ use well known CAESAR formalism
  [Banfi, Salam, Zanderighi '04]
▷ master formula for NLL resummation of rIRC safe global observables
  Note: similar work in MadGraph using SCET
  [Farhi, Feige, Freytis, Schwartz '15] [Balsinger, Becher, Shao '18]

Jet observable specifics

▷ modified wide angle behaviour
  [Dasgupta, Khelifa-Kerfa, Marzani, Spannowski '12]
  [Caletti, Fedkevych, Marzani, DR, Schumann '21]
▷ non-global logs [Dasgupta, Salam, '01]

Automation in SHERPA

▷ use available technology (PS integration, PDF evaluation etc.)
▷ interface to COMIX for colour exact insertions in multi-jet MEs
▷ final state fully differential in kin. and flavour → useful in matching
  [Banfi, Salam, Zanderighi '06] [Banfi, Salam, Zanderighi '10]

Soft Drop grooming effects

▷ well known in $v \ll z_{cut} \ll 1$ limit
▷ CAESAR-style formulas available
  [Baron, DR, Schumann, Schwanemann, Theeuwes '20]
Non-perturbative corrections

Setup for measurements: (i.e. CMS analysis in JHEP 01 (2022) 188)

- observables (i.e. jet angularities) measured on selected jet (leading $p_T$, $y$ range etc.)
- In different energy-scale bins (i.e. $p_T$ bin of selected jet)

Physical effects:

![Diagram showing cross section migration in $p_T$ for $\lambda_1$ in $Z +$ jet production]

- Shift between $p_T$ bins
- Shift in observable

$Z$+jet, anti-$k_t$, $R = 0.4$

$p_{T,jet} \in [120, 150]$ GeV

charged particles

NLO + NLL$'$ + NP

limit $p_T$ migration

no $p_T$ migration

NLO + NLL$'$ (PL)
Non-perturbative corrections

- define "transfer matrix" according to conditional probabilities
  \[ T(v_{HL}, p_T^{HL}|v_{PL}, p_T^{PL}) \]
- easily extracted from MC (here: SHERPA)
Z+jet $\sim$ quark jets

dijet $\sim$ gluon jets

ratio $\frac{\text{gluon}}{\text{quark}}$ of distribution means
data well described by MC@NLO and NLO+NLL$'$+NP
\Rightarrow challenges traditional "quarks are better understood than gluons"
Better understanding of soft drop grooming

- resummation around transition point $\rho \sim z_{\text{cut}}$
  
  [Benkendorfer, Larkoski, '21]

- relax strict $v \ll z_{\text{cut}} \ll 1$ assumption $\Rightarrow v, z_{\text{cut}} \ll 1$

- towards full consistent resummation across full observable range

Non-global logarithms at NLL

- first calculations in [Banfi, Dreyer, Monni '21], [Banfi, Dreyer, Monni '21]

- often neglected piece in NNLL efforts, but last missing piece for automated calculations? (for example in a framework like [Banfi, McAslan, Monni, Zanderight '15])
Summary

- jet substructure as a rapidly growing field with close interplay between
  - experiment
  - theory
  - construction of methods
  - Monte Carlo / parton shower development

- examples:
  - jet angularities w/ different parameters as playground
  - soft-drop grooming to eliminate UE/NP corrections $\rightarrow$ increase resummation regime

- Outlook:
  - automated NNLL?
  - range of groomed calculations?
  - NGLs?
Backup