Jet properties and substructure

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LHCP 2021, 7-12 June, online
Jets : a key tool at LHC

Jets have always been a key tool with numerous applications at colliders.

Butterworth, Davison, Rubin and Salam 2008

- Jet substructure emerged as a vibrant field since pioneering work in 2008.
- Provided momentum for several recent developments with impact on other areas too.

Annual “Boost” workshop series dedicated to boosted object studies.
Boosted object studies

Boosted regime implies studying particles with $p_T \gg M$. Hadronic decays often reconstructed as a single jet.

Use **substructure properties** to distinguish QCD jets from jets originating from boosted W, Z, H, t etc.

Several tools for tagging W/Z/H/t jets and for grooming (removal of UE/ISR, pile-up)
Some substructure tools over past decade *

Jet declustering

- Mass drop + Filtering
- Pruning
- Trimming
- Modified Mass Drop
- Soft Drop
- HEP Top Tagger
- JH Top Tagger
- Shower Deconstruction
- Qjets
- Lund Plane

Jet-shape/energy-flow

- N subjettiness
- Energy Correlation Functions
- Angularities
- Energy Flow Polynomials

* Not an exhaustive list
Substructure: early years and key questions

Marked by the creation of many tools studied exclusively via Monte Carlo simulations.
Substructure: early years and key questions

Substantial spread in shower predictions. Concerns about treatment of soft radiation and role of poorly understood non-perturbative effects.

How accurately is jet substructure described by state-of-the-art Monte Carlo tools?

Proceedings of Boost 2012
Valencia
Analytic understanding of substructure

2013 saw emergence of first analytic understanding of tools. MD, Fregoso, Marzani, Salam 2013

- Can jet substructure be predicted by first-principle QCD calculations and compared to data in a meaningful way?

Boost 2012 Valencia proceedings
mMDT – a unique jet observable

- Free from complex class of soft gluon effects (non-global logarithms)
- Small non-perturbative corrections

Precise analytic calculations & phenomenology

MD, Fregoso, Marzani, Salam 2013
Soft Drop: a robust and flexible tool

Generalises mMDT. **Robust** and **flexible** grooming tool which inherits the key properties of mMDT.

Today’s standard jet grooming tool with extensive applications in LHC experiments.

\[ z = \frac{\min(p_{t,i}, p_{t,j})}{p_{t,i} + p_{t,j}} \]

C/A decluster jet following harder branch until branching satisfies

\[ z > z_{\text{cut}} \theta^{\beta} \]

Larkoski, Marzani, Soyez, Thaler 2014
Substructure and precision QCD

- Soft Drop jet mass is most precisely calculated substructure observable.
- QCD predictions cover several orders of magnitude in jet mass
- Similar studies from CMS [arXiv:1807.05974]

Frye, Larkoski, Schwartz, Yan 2016
Marzani, Soyez, Schunk, 2017, 2018
Kang, Lee, Liu, Ringer 2018
Tagger performance and deep learning approaches

• Very active area with ML tools giving very high performance. Outperformed standard taggers.
• What features are learnt and are they well modeled by showers and detector simulations? How to get a handle on this?

De Oliveira, Kagan, Mackey, Nachman, Schwartzmann 2016
Kasieczka, Plehn, Russell, Schell 2016
The Lund plane  

Gustafson, Lonnblad, Andersson, Pettersson 1989

Useful way of representing emissions in a jet

Dreyer, Salam, Soyez, 2018

Density of emissions in primary Lund plane well understood theoretically.

At the heart of analytic approaches and parton showers. Can be used as an input to ML.

Bridges the gap between Deep learning and "Deep thinking" approaches?
QCD jets in the Lund plane

- Well understood theoretically
- Applications range from constraining event generator models to machine learning

\[
\rho \sim 2C_F \frac{\alpha_s(k_t)}{\pi}
\]

\[
\rho = \frac{1}{N_{\text{jet}} d \ln 1/\Delta d \ln k_t} \frac{d^2 N}{d \ln R/d \ln k_t}
\]

\[\sqrt{s} = 14 \text{ TeV}, p_t > 2 \text{ TeV} \]

Pythia8.230(Monash13)
Lund plane for tagging

Used both log-likelihood and machine learning approach.

Dreyer, Salam, Soyez, 2018

Based on Properties at each vertex

\[ \mathcal{T}_i = \{ \theta_i = \Delta_i, k_{t,i}, z_i, \varphi_i, \ldots \} \]

QCD rejection v. W efficiency

Pythia8 (Monash13)
hadron+MPI
Delphes+SPRA1
\( p_T > 2 \text{ TeV} \)

\( 1/\langle QCD \rangle \)

Ratio to Lund+log.lik.

\( \varepsilon_W \)
Performance and resilience

- Using information from full Lund tree gives significant performance gains.
- Trade off between performance and resilience to non-pert. effects
- Lund plane gives handle to increase resilience via a $k_t$ cut

Dreyer and Qu 2021

\[
\zeta = \left(\frac{\Delta \epsilon^2_W}{\langle \epsilon \rangle^2_W} + \frac{\Delta \epsilon^2_{QCD}}{\langle \epsilon \rangle^2_{QCD}}\right)^{-\frac{1}{2}}
\]
Lund plane phenomenology

Lund plane is a versatile tool.
- Useful to explore differences between parton showers
- Amenable to analytic calculations

ATLAS setup: $0.205 < \Delta < 0.287$

Includes resummation of single logarithmic terms matched to fixed-order

Lifson, Salam and Soyez 2020
Rethinking showers

- PanScales: a set of new dipole showers that remove issues seen with previous dipole showers (e.g. Pythia and DiRe v1 showers)
- First proven NLL accurate showers.
- Should represent a significant step for more reliable/accurate substructure description.

For extensions to include subleading colour and spin correlations: 2011.10054 and 2103.16526
Quantum interference effects in jet substructure

\[ \langle E(\hat{n}_1)E(\hat{n}_2)E(\hat{n}_3) \rangle \quad \theta_S \ll \theta_L \]

- EEEC observable probes QM interference effects within jets
- The azimuthal angle dependence reflects the role of spin correlations
- Analytic collinear resummation using light ray OPE formalism

Intrinisic theoretical interest

Chen, Moult, Zhu 2020
Spin sensitive observables and parton showers

- Azimuthal correlations defined using leading $k_t$ splitting in primary and secondary Lund plane
- New variables to test spin corr. in showers
- PanScales shower resummation for EEEC agrees with analytic.

Karlberg, Salam, Verheyen, Scyboz 2021
Summary

- Jet substructure has a central place in today’s LHC phenomenology
- Push and pull between desire for new powerful tools and reliability/robustness brings results (Soft Drop, Lund Plane…..)
- A rich phenomenology program with many interesting studies to come (talks by D. Recihelt (Theory), M. Seidel (CMS), R. Newhouse (ATLAS) and J. Mulligan (ALICE) at this meeting)
- Worth keeping an eye on ongoing developments in parton showers which are key to describing substructure
Extra Slides
Showers and substructure

• Standard dipole showers fail to reproduce QCD emission probability even for 2 emissions.
• A worry for methods that exploit correlation between emissions given by showers?

MD, Dreyer, Hamilton, Monni, Salam 2018
The Lund plane

Lund diagrams in the $(\ln z \theta, \ln \theta)$ plane are a very useful way of representing emissions.

Dreyer, Salam, Soyez 2018

Density of emissions in primary Lund plane well understood theoretically.

At the heart of analytic approaches and parton showers. Can be used as an input to ML.

Bridges the gap between Deep learning and “Deep thinking” approaches?
Basics: tagging and grooming

Simple underlying ideas behind many tools:

- Use asymmetric nature of QCD splitting. Single pronged QCD jet versus multi-pronged jets.
- Exploit singlet nature of W/Z/H suppresses soft large angle radiation.
- **Groom** jets to remove uncorrelated soft radiation: ISR, UE/pile-up