Jet properties and substructure

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Jet substructure

Jets play a central role at the LHC

Jet substructure exploits info on internal radiation pattern, many scopes:

- Tagging boosted objects
- UE/Pileup mitigation (grooming)
- QCD precision pheno
- Heavy-ion collisions
- Monte-Carlo generators
- Machine learning

Sketch from G. Soyez

In this talk
- Recent results that constrain the parton shower modelling and fixed-order calculations
- Few examples where quantum properties are exposed in new ways
Jet substructure using the clustering history

The Cambridge/Aachen algorithm sequentially combines the closest pairs.

The clustering history can be undone iteratively, following always the hardest branch.

At each step, two subjet prongs are obtained, \( j_1 \) and \( j_2 \), with \( p_{T,1} > p_{T,2} \).

where \( \theta \) is the angle between the prongs, \( k_T = \theta p_{T,2} \)
and \( z = p_{T,2} / (p_{T,1} + p_{T,2}) \)

The iterative declustering proceeds until substructure is found (grooming) or the jet can be fully declustered to study the kinematics of all the emissions (Lund jet plane).
The primary Lund plane: visualizing the parton shower

At leading order, emissions populate the plane uniformly and the running of the coupling sculpts the plane.

\[ d^2 P = 2 \frac{\alpha_s(k_{\perp}) C_R}{\pi} d\ln(z\theta) d\ln\left(\frac{1}{\theta}\right) \]

An all-order calculation is available: Lifson et al, JHEP 10 (2020) 170

Vast applications, as a tagger and as an observable!
The primary Lund plane with ATLAS

See talk by Robin Newhouse

The primary Lund plane with ATLAS

\[ \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1}, p_T > 675 \text{ GeV} \]

• Multiple physics effects contribute beyond the LO uniformly-filled plane
• However the measurement captures salient features of the q/g parton shower: the running of the coupling sculpts the plane

The primary Lund plane with ATLAS

Comparisons to MC generators

Parton shower \hspace{1cm} Hadronisation

Comparison to analytical calculations

ATLAS setup: $0.205 < \Delta < 0.287$

New all-order single log calculation of the Lund plane density including \textit{Lifson et al., JHEP 10 (2020) 170}

Precision of the Lund plane density 5-7\% at high $k_T$ while ~20\% at the edge of the perturbative region ($k_T \sim 5$ GeV)

Ability of the Lund Plane to isolate physics effects:
- PS effects (wide angles)
- hadronisation (collinear splits).

Input to (non)perturbative model development and tuning

New at LHCP
The primary Lund plane with ALICE

ALICE Preliminary

pp $\sqrt{s} = 13$ TeV

Charged-particle jets anti-$k_T$, $R = 0.4$

$|h_{jet}| < 0.5$, $20 < p_T^{ch}_{jet} < 120$ GeV/c

$\ln(k_T/GeV) \times 20-120 > 675$

$\max k_T (GeV) \times 5 > 135$

$\Delta R (rad) \times 0.1-R 0.005 - R$

ALICE ATLAS

$\ln(R/\Delta R)$

$(1/N_{jet})(dN/N_{emiss})(dln(k_T/GeV)/dln(R/\Delta R))$

ALICE-PUBLIC-2021-002.
The primary Lund plane with ALICE

• Similarly to ATLAS measurement, model uncertainties (Herwig vs PYTHIA in the response and matching purity/efficiency corrections) are dominant
• Some tensions in the moderately hard, moderately low angles (0.1-0.2 rad)
• Perturbative reach to be extended with triggered samples

New at LHCP
The Lund plane of heavy-quark jets: exposing the dead cone

- Iteratively decluster jets with a fully reconstructed $D^0$ among its constituents
- Follow always the prong containing the $D^0$
- Register the splitting energy $E_{\text{radiator}}$ and the splitting $k_T$ at each step

Define:

$$R(\theta) = \frac{1}{N_{D^0\text{jets}}} \frac{dN^{D^0\text{jets}}}{d\ln(1/\theta)} \left/ \frac{1}{N_{\text{inclusive jets}}} \frac{dN^{\text{inclusive jets}}}{d\ln(1/\theta)} \right|_{k_T, E_{\text{radiator}}}$$

The deepest levels of the jet tree are splittings at small angles/lower energies
- most sensitive to mass and the dead cone effect

$E_{\text{radiator}} =$ energy of the splitting prong at each declustering step

The Lund plane of heavy-quark jets: exposing the dead cone

ALICE, arXiv:2106.05713

- Suppression of emissions at low angles for $D^0$ jets as compared to inclusive jets
- Smaller effects for higher splitting energy
The Lund plane of heavy-quark jets: exposing the dead cone

ALICE, arXiv:2106.05713

- Suppression of emissions at low angles
- Smaller effects for higher splitting energy

Future:
mass scan of the effect: B jets, top quark
Grooming

Groom away branches in order to access hard parts of the jet that are under better theoretical control

• mMDT/SofDrop grooming
  Remove branches of an angular-ordered clustering tree until you find a splitting that satisfies:

  \[ z_g = \frac{\min(p_{t,1}, p_{t,2})}{p_{t,1} + p_{t,2}} > z_{\text{cut}} \left( \frac{\Delta R_{12}}{R_0} \right)^\beta \]

• New: Dynamical Grooming
  1. Select the hardest branch in the C/A sequence
  2. Drop all branches at larger angles

  \[ \kappa^{(a)} = \frac{1}{p_T} \max_{i \in \text{C/A}} z_i (1 - z_i) p_{T,i} (\theta_i/R)^a \]

  More aggressive grooming with decreasing parameter a


Larkoski et al, JHEP 05 (2014) 146
(Recursive SD) Dreyer et al, JHEP 06 (2018) 093

Groomed-away areas can be drawn as exclusion regions in the Lund Jet Plane

New at LHCP
The groomed momentum balance

\[ z_g = \frac{p_{T2}}{p_{T1} + p_{T2}} \]

Low \( p_T, R \) dependence

- ALICE Preliminary, pp \( \sqrt{s} = 13 \text{ TeV}, L_{int} = 11.5 \text{ nb}^{-1} \)
  - Anti-k_T, 30 GeV/c < \( p_T \) < 40 GeV/c
  - \( p_T > 0.15 \text{ GeV/c}, E_{\text{clus}} > 0.3 \text{ GeV} \)
  - \( |y^{\text{track}}| < 0.7, |y^{\text{cluster}}| < 0.7, |y^{\beta}| < 0.7 - R \)
  - SoftDrop: \( z_{\text{cut}} = 0.1, \beta = 0 \)
  - \( R = 0.2 \)
  - \( R = 0.3 \)
  - \( R = 0.4 \)
  - \( R = 0.5 \)

Data / MC

- PYTHIA Perugia 2011

High \( p_T, \) large \( R=0.8, \) more grooming

- ATLAS \( \sqrt{s} = 13 \text{ TeV}, 32.9 \text{ fb}^{-1} \)
  - Track-based, anti-k_T, \( R = 0.8 \)
  - Soft Drop, \( z_{\text{cut}} = 0.1, \beta = 0 \)
  - \( p_T > 300 \text{ GeV} \)

Data
- Pythia 8.186
- Sherpa 2.1
- Herwig++ 2.7

Ratio to Data

High \( p_T, \) large \( R=0.8, \) less grooming

- ATLAS \( \sqrt{s} = 13 \text{ TeV}, 32.9 \text{ fb}^{-1} \)
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Ratio to Data

Largest discrepancies in the regions most affected by non pert. effects
(higher \( \beta \), low \( z_g \))

\( z_g \) exposes the QCD splitting function


Low \( z_g \) affected by non pert. effects (UE)

More soft subleading prongs at large \( R \)

The groomed jet radius

\[ \theta_g = \frac{\Delta R(j_1, j_2)}{R_0} \]

Good description by MC generators
Largest discrepancies with less grooming in the regions most affected by non-perturbative effects (collinear splits)
See talk of James Mulligan for observables that measure the angle between jet axes found with different recombination schemes (see also backup)

*Phys. Rev. D 101, 052007 (2020)*
First measurement of dynamical grooming
Good agreement between PYTHIA and data
At high $k_T$, different dyn grooming settings seem to select the same splitting
First comparisons to analytical calculations at LO+N2DL accuracy

Caucal et al, arXiv:2103.06566
Dynamical grooming

- First measurement of dynamical grooming
- Good agreement between PYTHIA and data
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- First comparisons to analytical calculations at LO+N2DL accuracy

Caucal et al., arXiv:2103.06566
The groomed jet mass: precision QCD

\[ \rho = 2 \log_{10} \left( \frac{m_j}{p_{T,j} R} \right) \]

- The calculations are able to describe the data in the resummation regime at the level of 10%
- See also CMS comparisons of groomed and ungroomed mass [CMS, JHEP 11 (2018) 113]
- Rg comparison to NLL calculations also available (see backup)
At LO, LHA, Width, Thrust, Multiplicity, are expected to be higher in gluon-enriched samples

Quark and gluon initiated jet showers not well described by generators, important consequences for taggers
Quark fragmentation with LHCb

See talk by Martin Kucharczyk

Jet shapes of jets recoiling from Z boson in the forward region, quark enriched

- PYTHIA underestimates number of high-z/low-r hadrons
- PYTHIA underestimates the charged hadron multiplicity
- Qualitative comparisons to ATLAS central measurements point to harder and more collimated fragmentation in the forward region

2.5 < η_{jet} < 4

Heavy flavour jet substructure

- Groomed momentum imbalance more asymmetric for D^0-tagged jets, consistent with a harder fragmentation than inclusive jets
- $R_g$ consistent with inclusive jets: less sensitivity to small angles compared to full declustering
- Fewer (SD) emissions in the D^0-tagged jets measured via the $n_{SD}$ (or $n_{LH}$), consequence of both color factors and mass effects
Most of the considered substructure observables are strongly correlated.

Useful to select a set of minimally correlated variables: \( R_g, z_g, \) multiplicity, \( \epsilon \)

And study the best \( \alpha_S(m_Z) \) that describes the data.

This kind of consideration has broad scope!
Correlation of substructure observables

Most of the considered substructure observables are strongly correlated

Useful to select a set of minimally correlated variables: \( R_g, z_g, \) multiplicity, \( \epsilon \)

And study the best \( \alpha_S(m_Z) \) that describes the data

- \( z_g \) independent on \( \alpha_S(m_Z) \) (LO expectation)
- Multiplicity expected to be highly affected by non pert. effects
- \( R_g; \) lower impact of non pert. radiation, sensitivity to \( \alpha_S(m_Z) \)

\[ CMS, \ Phys.\ Rev.\ D \ 98 \ (2018) \ 9, \ 092014 \]
What about colour flow?

Pull angle: measurement of how much the radiation pattern from one jet leans towards another.

Color flow not well constrained in QCD.

Color info could complement kinematic properties to select specific topologies.

New IRC-safe version (pull magnitude and projections)

Larkoski et al, JHEP 01 (2020) 104

A note on calorimetric vs track-based results

Track-based measurements are more precise due to the angular resolution of tracks.

Relevant question with substructure entering precision regime: can jet substructure be formulated in a manner that facilitates more precise calculations?

• Track functions: Chan et al Phys. Rev. Lett. 111 (2013) 102002

• Interesting proposal that incorporates non-perturbative info from tracks or charges into pert. calculation and connects to formal developments in QFT
  Chen et al, Phys. Rev. D 102, 054012 (2020)
Conclusions and prospects

New techniques like grooming or the iterative declustering allow to isolate different physics effects and constrain
the parton shower. A prominent example is the Lund Jet Plane.

Beyond utility for searches and constraining SM calculations, new techniques expose building blocks of QCD like
the splitting function, or quantum properties like the dead cone effect or the color flow.

Interesting developments for using track-based measurements as precision tests of the SM.

Not discussed here, check out recent results on jet substructure in heavy-ion collisions in talks by Laura Havener,
Robin Newhouse, James Mulligan, Helena Pintos, and many other interesting results on event shapes, inclusive/multi-jet production and correlations, Z boson and jets and more in talks by Salim Cerca, Tibor Zenis,
Martin Kucharczyk.
Other relevant recent results

CMS, <35.9 fb⁻¹ (13 TeV)

196 < p_T < 272 GeV

548 < p_T < 638 GeV

IRC-safe ratios of jet cross sections for different resolution R

CMS,HEP 12 (2020) 082
Measuring the angle between different jet axes

See talk by James Mulligan

• Strong correlation between SD and E-scheme axes
• More aggressive grooming ($\beta=0$) \( \rightarrow \) larger $\Delta R_{axis}$ for SD and E-scheme
• Negligible dependence on grooming condition for WTA–E-scheme
• Differences sensitive to soft radiation pattern

Cal et al., JHEP 04 (2020) 211
$R_g$ compared to analytical calculations

NLL calculation by Kang et al JHEP 02, 054 (2020)
Hadronisation
The Lund plane, ALICE

- **ALI-PREL-479212**
- **ALI-PREL-479188**

**Graphs:**
- Left: Distribution of $dN/d(k_T/GeV)$ versus $\ln(k_T/GeV)$ with $0 < \ln(R/\Delta R) < 1.4$, $0.1 < \Delta R < 0.4$.
- Right: Distribution of $dN/d(k_T/GeV)$ versus $\ln(R/\Delta R)$ with $-1.0 < \ln(k_T/GeV) < 1.5$, $0.4 < k_T < 4.5$ GeV/c.

**Legend:**
- PYTHIA8 Monash
- Herwig 7
- Sherpa (AHADIC)
- Sherpa (Lund)
- $pp$ $\sqrt{s} = 13$ TeV
- Charged-particle jets
- $|\eta_{\text{jet}}| < 0.5$
- $-|\eta_{\text{jet}}|< 0.5$
- $20 < p_{T,\text{jet}}^{\text{ch}} < 120$ GeV/c.

**Note:**
- Systematic uncertainty $20 < p_{T,\text{jet}}^{\text{ch}} < 120$ GeV/c.