Novel probes of QCD: Precision Jet Substructure at the LHC

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o.b.o. the ATLAS, CMS, LHCb & ALICE Collaborations

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Northeastern University, Boston, USA
One reason that QCD is fascinating because it demonstrates *emergent behaviour* —

just because you know the QCD Lagrangian doesn’t mean you understand all of its physics!

\[
\mathcal{L}_{\text{QCD}} = -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu a} + \bar{\psi} i \gamma^\mu \psi
\]

During Run 2 of the LHC, all four large collaborations are testing QCD using a novel techniques in a challenging setting:

*within jets!*

... and by *working closely with our hep-ph colleagues*, they’re doing it with higher precision than ever before!
## Precision JSS @ LHC Run 2

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z_{SD} and $N_{SD}$  

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCJetSubstructureMeasurements
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**Today!**
Outline

1. **Why is Jet Substructure interesting to study now?**
   — Theoretical progress following the development of the Soft Drop / mMDT grooming algorithm.

2. **Where have we tested these new predictions?**
   — Jet mass measurements from ATLAS and CMS.

3. **What is the future of precision JSS?**
   — New directions from ALICE and LHCb in ions and quarkonium production.
Jets have long been used as probes of QCD, however high-precision calculations of their **substructure** were unavailable.

- Jets have a hard boundary — divergent **non-global logarithms** blocked theoretical progress!

- The **Soft Drop / mMDT** algorithm provided a way to remove **soft and wide-angle radiation** from jets: it is **formally insensitive to NGLs**.

- For more details on state-of-the-art JSS calculations, see F. Ringer and Y.-T. Chien here @ DPF19-QCD.
1. Begin with an anti-kt jet.

2. Recluster jet constituents using Cambridge/Aachen (C/A) algorithm (angular-ordering).

3. Iterating inward from widest-angle radiation, discardsubjets when they fail the Soft Drop condition.
   - Two parameters: $z_{\text{cut}}$ and $\beta$.

4. When the SD condition is satisfied, stop!
   - Soft and Wide-Angle radiation is removed.

Larkowski, Marzani, Soyez, Thaler, JHEP 1405 (2014) 146
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Larkowski, Marzani, Soyez, Thaler, JHEP 1405 (2014) 146  
M. LeBlanc (Arizona) — Precision JSS at the LHC — 2019 APS DPF — Slide 8
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Larkowski, Marzani, Soyez, Thaler, JHEP 1405 (2014) 146  
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Soft Drop / mMDT

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Larkowski, Marzani, Soyez, Thaler, JHEP 1405 (2014) 146
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Soft Drop Jet Mass

• The first JSS observable to understand is the Soft Drop jet mass for light-quark & gluon jets.
  • ~0 @ LO, sensitive to higher-order physics.
  • First calculations @ >LL were available for the mass, and it still leads the pack in terms of precision.
  • Different effects in QCD factorise naturally as a function of the mass.
    • Calculations are valid in the resummation (intermediate mass) region.

NP-QCD Resummation Fixed-Order

Soft Drop Groomed Mass
Soft Drop, $z_{\text{cut}} = 0.1$, $\beta = 0$
13 TeV, $pp \rightarrow Z+j, p_{TJ} > 500$ GeV, $R = 0.8$

Herwig++ (no had+ue)
Herwig++ (had+ue)
NNLL matched

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NLO+NLL: Kang, Lee, Liu, Ringer; JHEP (2018) 137
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**Soft Drop Jet Mass**

- **Goal:** unfolded jet mass spectrum in data, which can be compared to new precision QCD calculations.

- **Challenge:** non-trivial detector effects to account for in unfolding.

- This distribution will be sensitive to physics modelling of constituent-level effects!

  - *i.e.* calorimeter granularity, splitting/merging, PFO algorithms, *etc.*, *etc.*
SD Mass: Systematics

**ATLAS — "Bottom-Up"**

- Several systematics on the modelling of ATLAS topo-clusters (efficiency, energy scale & resolution) are derived from earlier measurements of the single-hadron response (E/p).
- Complex: requires understanding of any collective effects arising due to dense environment.

**CMS — “Top-Down”**

- Jet mass scale & resolution estimated from the hadronic W peak in top-pair events.
- Simpler scheme, but requires extrapolation across topologies.

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Good agreement in the **resummation region**, where these calculations are expected to be valid. The **NP region appears to be more difficult to describe**, both analytically and for MC programs.
The Lund Jet Plane

A jet may be approximated as **soft emissions** around a **hard core** which represents the originating quark or gluon.

These emissions can be parameterised by their **relative momentum fraction**, \( z \), and angle of emission relative to the jet core, \( \Delta R \).

The Lund Plane is the phase space of these emissions: it naturally factorises perturbative and non-perturbative effects, UE/mpi, collinear splittings, etc.

\[
\text{The jet mass is just one diagonal line in this space...}
\]

\[
\text{m} \sim z^* \Delta R^2
\]
Methodology

1. C/A Reclustering:
Combine closest pairs of charged particles or tracks!

2. C/A Declustering:
Unwind, widest angles first. Each step is an emission, or, a point in the Lund Jet Plane!

Emissions at detector- & truth-level are geometrically matched when constructing the response matrix.

An iterative Bayesian unfolding procedure is applied to correct for acceptance and detector resolution effects, with 4 iterations.
Various Monte Carlo simulations are compared to the unfolded data. None are compatible across the entire 2D space. In particular:

- **Hadronization effects** are large for non-perturbative emissions.
- **Parton shower effects** are large for wide-angle emissions.

Precision of ~10% or better is achieved throughout most of the Lund jet plane. The largest source of uncertainty is typically due to Monte Carlo modelling effects or the jet energy scale.

Over 115 million jets are included in this measurement!
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Prompt $J/\psi$ Polarisation

- $J/\psi$ production occurs at the pQCD-npQCD threshold: a sensitive handle on this complex region.

- Different $J/\psi$ production mechanisms:
  - prompt, feed-through (ME) and via B-hadron decay (PS).

- Differential prompt-$J/\psi$ production cross-sections @ Tevatron, LHC well-described by analytical NRQCD calculations ... 
  - ... but, these predict large transverse polarisation which is not observed in data!

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LHCb $J/\psi$ in Jets

- Measurement of the momentum fraction carried by $\sim$2 million $J/\psi$ candidates produced within forward anti-$k_t$ jets reconstructed by LHCb.

- $p_T > 20$, $2.5 < |\eta| < 4.0$, $R=0.5$.

- Prompt $J/\psi$ decays distinguished from those originating from $B$ hadron fragmentation using decay lifetime.

LHCb $J/\psi$ in jets

- Unfolded $z(J/\psi)$ distributions are provided:
  - Good agreement with Pythia for $J/\psi$ originating from $B$-hadron decay.
  - Prompt $J/\psi$ results do not agree with fixed-order NRQCD.
  - Prompt $J/\psi$ are noted to be less isolated than expected.
  - If high-pT $J/\psi$ are produced by parton-showers rather than the hard scattering, deficiency of polarisation & isolation could be accounted for!
ALICE: $z_g$ and $N_{SD}$

- Track-based studies in the context of Pb+Pb and pp collisions.

- Examining the possible quenching effects on JSS, using iterative declustering.

- **Observable**: $N_{SD}$, the “Soft Drop Multiplicity” — length of primary C/A declustering sequence after SD.

- **Key question**: colour coherence.
  “When can a colour dipole be resolved by the medium as two independent colour charges?”

- **Observable**: $z_g$, the $p_T$ balance of the hard splitting which satisfies the SD condition.

\[ z_g = \frac{p_{T2}}{p_{T1}} \]
Results for low-pT track-jets in \( pp \) collisions are unfolded to particle level in order to account for acceptance & detector effects.

Good agreement is observed in the bulk of the distributions, though some effects do not seem to be well-modelled by any MC.

Main systematics arise due to tracking efficiencies & unfolding.

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<tr>
<th>Observable</th>
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<th>( n_{SD} )</th>
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<td>Interval</td>
<td>0.1–0.175</td>
<td>0.25–0.325</td>
</tr>
<tr>
<td>Tracking efficiency (%)</td>
<td>1.9</td>
<td>0.2</td>
</tr>
<tr>
<td>Prior (%)</td>
<td>+0.0</td>
<td>+0.6</td>
</tr>
<tr>
<td>Regularisation (%)</td>
<td>−1.8</td>
<td>−0.0</td>
</tr>
<tr>
<td>Truncation (%)</td>
<td>+0.8</td>
<td>+0.2</td>
</tr>
<tr>
<td>Binning (%)</td>
<td>+2.2</td>
<td>+1.8</td>
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<tr>
<td>Total (%)</td>
<td>−0.5</td>
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ALICE, submitted to PLB [arXiv:1905.02512]
Interpretation: the larger the opening-angle, the more resolved the splittings are — wide-angle splittings are more suppressed by the medium!

More modification than predicted is reported by reference samples for larger angular separations of the subjets.

Trend in data towards lower $N_{SD}$ than in reference.
Concluding remarks

- ATLAS, CMS, LHCb and ALICE have all established precision JSS measurement programmes with Run 2 data.
  - Probing QCD inside jets with higher precision than ever before!
  - Diverse analyses all provide different insights:
    - Measurements of the jet mass by ATLAS and CMS have been compared to the most precise calculations of jet substructure available, informing the development of our analytical understanding of JSS.
    - A new measurement of the Lund jet plane is designed to factorise physical effects, and will be made available for Monte Carlo tuning efforts before Run 3.
    - LHCb is revisiting the J/Psi polarisation question from a new point of view.
    - ALICE has presented a new measurement of $z_g$ and $N_{SD}$ in $pp$ and Pb+Pb, exploring questions related to colour coherence and the QGP.
  - Please come find me to chat this week if you are interested in precision JSS and want to learn more, or get involved!

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@TopPhysicist

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Thanks for your attention!

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCJetSubstructureMeasurements

For more JSS, see last week’s agenda from BOOST 2019 @ MIT: https://indico.cern.ch/event/753914/
Auxiliary material.
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<td>ATLAS-CONF-2019-035</td>
<td>CMS-PAS-TOP-19-005</td>
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https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCJetSubstructureMeasurements

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Soft Drop Jet Mass

ATLAS

\(J^3 = 13 \text{ TeV}, 32.9 \text{ fb}^{-1}\)

anti-\(k_t\), \(R=0.8\), \(p_T^{\text{lead}} > 600 \text{ GeV}\), Data

Soft drop \(\beta = 0\), \(z_{\text{cut}} = 0.1\)

CMS

2.3 \text{ fb}^{-1} (13 \text{ TeV})

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CMS, JHEP 11 (2018) 113
Soft Drop Unfolding Matrices

- Recall: Iterative Bayesian unfolding, 4 iterations.
LHCb $J/\psi$ in jets: unfolding matrices

The ATLAS Collaboration

A diverse collaboration with >5500 members: ~3000 signing authors, plus engineers, technicians, etc!

2016 ATLAS Gender & Geographic Diversity Study: ATL-GEN-PUB-2016-001
Reconstructing the Lund Jet Plane

1. C/A Reclustering:
Combine closest pairs of charged particles or tracks!

2. C/A Declustering:
Unwind, widest angles first. Each step is an emission, or, a point in the Lund Jet Plane!

"Secondary Planes" are not considered in this result.

Iterative declustering approach to approximate the plane, proposed by Dreyer/Soyez/Salam 1807.04758

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