Searching for Moliere scattering with jet substructure observables

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Resolving medium scales

- What are the **relevant length scales in the medium**?
- Which substructure observables sensitive to **which medium properties**?

**Emergent structure, such as quasi-particles?**

**What can the medium resolve?**
Moliere scattering and the quark-gluon plasma

- Search for emergent medium structure via point-like single hard scattering
  - Concept: Rutherford-like scattering exp.
    - Broadening $\sim$ Gaussian
    - Single hard scattering: power law tail ($\sim 1/k_T^4$)
- Goal: unambiguous experimental signal
  - In practice, models needed to interpret fully

F. D’Eramo et al, JHEP 05 (2013) 031, JHEP 01 (2019) 172, etc
Caucal, Mehtar-Tani, PRD.106 (2022) 5, L051501, JHEP 09 (2022) 023, ...
Searching via jet deflection

- Traditional approach: jet acoplanarity
- Search for excess yield at large deflection
- Can replace trigger with $\gamma$, $Z$
Experimental searches via jet deflection

Traditional approach: jet acoplanarity


ALICE: JHEP 09 (2015) 170

CMS: PRL 119, 082301 (2017)

No evidence for point-like scattering
Recent progress on jet deflection

- Inconsistent with Moliere scattering
- Consistent with medium response

**ALI-PUB-555709**


Recent CERN seminar, J. Norman
Alternative: searches via jet substructure

- Complementary search possible via **subj jet deflection**
- Open questions:
  - Ideal observables?
  - Can be identified...?

**For today:**

1. **Optimal way to find the relevant splittings?**
2. Search for **high $k_T$ emissions** via groomed substructure as **signature of point-like scattering**
3. **Next generation** of groomed substructure measurements: $\gamma$-tagged $R_g$

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Identifying hard splittings: Soft Drop

- \( k_T = p_T^{\text{sublead}} \sin \Delta R \)
- Iteratively follow splitting tree

**Soft Drop**

Larkoski et al., JHEP 05 (2014) 146

\[
\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{\text{cut}} \left( \frac{\Delta R}{R} \right)^{\beta}
\]

- \( z_{\text{cut}} = 0.2 \)
- \( \beta = 0 \)
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- $z_{\text{cut}} = 0.2, 0.4$
- $\beta = 0$
- $z_{\text{cut}} = 0.4$ trades phase space to focus on **angular dependence**
Identifying hard splittings: Dynamical Grooming

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- Iteratively follow splitting tree

Dynamical Grooming

Mehter-Tani et al., PRD.101.034004

$$\kappa^a \propto \max_{i \in C/A} \left[ z_i (1 - z_i) p_{T_i} (\Delta R_i / R)^a \right]$$

- $a = 0.5$: "core" - more sym., narrow

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- In practice, need $\min k_T$ in Pb–Pb
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• In practice, need \( \min k_T \) in Pb–Pb
• Alternatively, add \( z \) requirement (0.2)
Emplo"ving the grooming methods

• Consider $p_T^{\text{ch}}_{\text{jet}} = 60 \text{ GeV}/c R = 0.2 \text{ jet}$
• Decluster with C/A, select iterative splittings:
  1. $z = 0.175, \Delta R = 0.4, k_T = 4.09 \text{ GeV}/c$
  2. $z = 0.2, \Delta R = 0.3, k_T = 2.93 \text{ GeV}/c$
  3. $z = 0.4, \Delta R = 0.2, k_T = 3.15 \text{ GeV}/c$
  4. $z = 0.1, \Delta R = 0.1, k_T = 0.24 \text{ GeV}/c$

→ Which method selects which splitting?
Employing the grooming methods

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Which method selects which splitting?
- **DyG $\alpha = 1.0$: #1**
Employing the grooming methods

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Which method selects which splitting?
- DyG $a = 1.0$: #1
- SD $z_{\text{cut}} = 0.2$: #2
Employing the grooming methods

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→ Which method selects which splitting?
  - DyG $a = 1.0$: #1
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  - DyG $a = 1.0, z > 0.2$: #3
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  • DyG $a = 1.0, z > 0.2$: #3
  • SD $z_{\text{cut}} = 0.4$: #3
Comparing grooming methods in pp

- Shape variations at low $k_T$
- Grooming methods converge at high $k_{T,g}$
- $z$ requirement dominates over grooming method
- PYTHIA in broad agreement with data
- Additional $R +$ further models in backup

See also: $R_g + z_g$ with DyG:
ALICE, JHEP 05 (2023) 244

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Unfolding Dynamical Grooming in Pb–Pb

- Dynamical Grooming exhibits **reduced subleading subjet purity** in Pb–Pb
- **Off-diagonal mismatched splittings** are major component at low $k_T$
  - **Problematic for unfolding**
- Caused by **requirement to always select a splitting**
- **Address by minimum measured $k_T$ requirement**
- Trade **improved purity** for **reduced dynamic range** and kinematic efficiency
- **Minimum $z$** has similar impact
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Comparing grooming methods in Pb–Pb

- **First DyG in Pb–Pb**
- **Similar trends** in 0-10% and 30-50%
- Reduced SD $z_{\text{cut}} = 0.4$ yield due to phase space
- **Consistent set of splittings** from all DyG $a = 1.0$, SD $z_{\text{cut}} = 0.2$
  → Suggests few hard splits further into tree
Searching for modification

- No enhancement at high $k_{T,g}$
- Standard DyG shows little modification
Searching for modification

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- **Modification** in methods with $z > 0.2$
  - Larger modification in 0-10%
- Consistent with narrowing picture seen in many substructure analyses.
  - eg. $R_g$, jet axis difference, angularities, etc
- **No clear evidence of Moliere scattering**
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- No clear evidence of Moliere scattering
- 0–10% data described by JETSCAPEv3.5 AA22$^1$ and Hybrid model$^2$ w/out Moliere

1: JETSCAPE arXiv:2301.02485
2: D’Eramo et al. JHEP 01 (2019) 172, Hulcher et al. QM 22

ALICE Preliminary
pp, Pb–Pb $\sqrt{s_{NN}} = 5.02$ TeV
Anti-$k_T$ ch-particle jets
$R = 0.2$, $|\eta_{jet}| < 0.7$
$60 < p_{T, ch jet} < 80$ GeV/c

Soft drop $z_{cut} = 0.2$
Interpreting modification

- No clear modification → No evidence for point-like single hard scattering
  - Possible competing effects: signal on top of energy loss
- JETSCAPE (inc. Moliere) and Hybrid w/o Moliere both describe data.
- Caveat: pp baseline
- Now what...?
  → Look to other substructure observables

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Soft drop $z_{\text{cut}} = 0.2$
Inclusive groomed jet radius, $R_g$

- Characterize QGP resolution scale via angular dependence of hard splittings
- **Consistent picture** for ALICE + ATLAS
- Promotes narrow or filters out wider subjets
- Incoherent energy loss effects may indicate medium resolving the splittings? Or changing q/g fraction? Or “survival bias”?
**γ-tagged angular substructure**

- Disentangle via **γ-tagged substructure**
  1. **Quark enhanced sample**
  2. Access **initial hard scattering momentum** (eg. \(\sim\) unquenched \(p_{T,jet}\))

- CMS recently measured angular-dependent observables, CMS-PAS-HIN-23-001:
  - \(R_g\) with SD \(z_{cut} = 0.2\)
  - Jet girth: \(g = 1/p_{T,jet} \sum_i p^i_T \Delta R_{i,jet}\)
  - \(p_T^γ > 100\) GeV/c, \(R = 0.2\)
  - Selection two regions in \(x_{jγ}\):
    1. **More quenched**: \(x_{jγ} = p_{T,jet}/p_T^γ > 0.4\)
    2. **Less quenched**: \(x_{jγ} > 0.8\)
Studying less quenched jets

• Less quenched jets ($x_{j\gamma} > 0.8$) show similar behavior as inclusive jets

• Suggests consistent selection bias in both measurements

• Mixed description by Hybrid model

• Moliere preferred for $g$, w/o preferred for $R_g$
And more quenched jets?

- More quenched jets \((x_{jj} > 0.4)\): no narrowing
- w/ Moliere preferred
  - Tension at large \(g\)
- No sensitivity to wake
- Strongly suggests narrowing due to survival bias
Interpreting more quenched jets

- Disappearance of narrowing as anticipated

- What remains in $x_{jγ}$ dist.? 

- Disentangle energy loss and rare point-like scattering in $R_g$? Next to $k_{T,g}$?
Where are we and what’s next?

- **What can serve as an unambiguous signal?**
  - Preferred model between $k_{T,g}$ and $y$-tagged $R_g$ highlights difficulty
- **Bayesian inference** w/ Hybrid model?
  - Model dependence caveats, etc
- **Overly simple mental model?**
  - Not sensitive enough? Wrong region of phase space?

**Next steps**

- Low $p_T$ signal may be clearer. **Mixed events?** ML?
- $y$-tagged $k_{T,g}$?
- **New unambiguous observables** sensitive to Moliere?
Summary

- **Comprehensive studies** searching for Moliere scattering via jet substructure

1. **Modification of** $k_{T,g}$, similar to narrowing seen in other substructure observables
2. **No clear evidence of** Moliere scattering in inclusive jets
3. **Narrowing disappears for** $\gamma$-tagged jets
   - Suggests **survival bias** in inclusive jets case leads to narrowing
4. **Model dependent Moliere signal in** $\gamma$-tagged $R_g$
   - Not unambiguous + tension with $k_{T,g}$

Careful choice of next steps is critical
Summary

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Careful choice of next steps is critical
Backup
• Jets are **experimentally challenging** due to **large uncorrelated background** from underlying event
  • Fluctuations can be $\sim \rho_{T,\text{jet}}$
• Substructure **especially susceptible**
  → **Careful bkg subtraction is critical!**

• Exp. approaches (not exclusive):
  • Subtract **event-by-event bkg**, unfold
    • Bkg fluc. limits accessible kinematics
  • **Jet grooming** aims to removes uncorrelated bkg (contamination?)
  • **Reduce bkg sensitivity or size**
  • Rethink problem: **statistical + correlation methods** remove bkg on ensemble level
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NOTE: Selections are a bit different, unfolded vs smeared
ALICE jet deflection $R = 0.4$
Dynamical Grooming: Lund Planes

Mehtar-Tani et al., PhysRevD.101.034004
Comparing grooming methods in pp: mixed methods, $R = 0.4$

ALICE Preliminary
pp $\sqrt{s} = 5.02$ TeV
Anti-$k_T$ charged jets
$R = 0.2, |\eta_{jet}| < 0.7$
$60 < p_{T,ch \text{ jet}} < 80$ GeV/c

$1/N_{jets}dN/dk_{T,g}(\text{GeV/c})^{-1}$

Method
SD $z_{cut} = 0.2$
SD $z_{cut} = 0.4$
DyG $a = 1.0$
DyG $a = 1.0, z = 0.2$

$k_{T,g}$ (GeV/c)

ALICE Preliminary
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$60 < p_{T,ch \text{ jet}}^{ch} < 80$ GeV/c

$1/N_{jets}dN/dk_{T}(\text{GeV/c})^{-1}$

Method
$k_T$Drop
timeDrop
Leading $k_T$
Leading $k_T z > 0.2$

PYTHIA8 Monash 2013

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Dynamical Grooming: analytical calculations pp

DyG – $a = 1$

- ALICE
- LO+N²DL’
- LO+N²DL’+NP

DyG – $a = 2$

- $60 < p_T^{ch} < 80$ GeV
- $|\eta| < 0.5$, anti-$k_\perp (R = 0.4)$

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Dynamical Grooming in Pb–Pb

- **First measurements** of Dynamical Grooming in Pb–Pb
- Grooming methods converge at high $k_{T,g}$
- Smaller bkg extends $k_{T,g}$ range in semi-central

![Graphs showing dynamical grooming in Pb–Pb](image)
How do models fare?

- SD 0.2
- MATTER + LBT
- Describes data well

**Hybrid model**
- D’Eramo et al. JHEP 01 (2019) 172
- Hulcher et al. QM 22
- With, w/out Moliere
- w/out Moliere describe 0-10% data better

**Caveat:** pp baseline

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Angle between jet axes

\[
\Delta R_{\text{axis}} = \sqrt{(y_1 - y_2)^2 + (\phi_1 - \phi_2)^2}
\]

- Jet quenching **disrupts transverse jet structure**
  - Weight contributions to **resolve angular scales**, inc. effect of soft radiation
- **Narrower jets** found in Pb–Pb relative to pp
- Jet axis **insensitive to grooming**
- Qualitatively describe by most models
- **Similar conclusion** as \(R_g\)

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ALICE Preliminary
\[\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}\]

Ch-particle jets, anti-\(k_T\)

40 < \(p_T^{\text{ch, jet}}\) < 60 GeV/c
\(R = 0.2\) \(|\eta_{\text{jet}}| < 0.7\)
Angle between jet axes

\[ \Delta R_{\text{axis}} = \sqrt{(y_1 - y_2)^2 + (\phi_1 - \phi_2)^2} \]

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