

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:



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 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 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, **j1** and **j2**, with $p_{T,1} > p_{T,2}$

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



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



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

Vast applications, as a tagger and as an observable!

Dreyer et al, JHEP 12 (2018) 064

QCD Splitting probability

$$d^2 P = 2 \frac{\alpha_s(k_\perp) C_R}{\pi} dln(z\theta) dln(\frac{1}{\theta})$$

The primary Lund plane with ATLAS

See talk by Robin Newhouse



ATLAS, Phys.Rev.Lett. 124 (2020) 22, 222002





The primary Lund plane with ATLAS



•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 Hadronisation ATLAS $\frac{1}{N_{\text{jets}}} \frac{d^{\text{-}}N_{\text{emissions}}}{dln(R/\Delta R) dln(1/z)}$ $\sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1}$ p_{T.1} > 675 GeV 2.2.5 (AHADIC 1.80 < ln(1/z) < 2.08 wig 7.1.3 (Ang. ord. erwig 7.1.3 (Dipole) Ratio to Data 0. Relative Uncertainty $\ln(R/\Delta R)$ 10^{-2} **10**⁻¹ $\Delta R = \Delta R$ (emission, core)

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

Input to (non)perturbative model development and tuning

Comparison to analytical calculations



New all-order single log calculation of the Lund plane density including *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 ~5 GeV)





The primary Lund plane with ALICE



ALI-PREL-480020

New at LHCP

	ALICE	ATLAS
$p_{T,jet}$ (GeV)	20-120	>675
$\max k_T$ (GeV)	5	>135
ΔR (rad)	0.1- <i>R</i>	0.005 - F

<u>ALICE-PUBLIC-2021-002.</u>





The primary Lund plane with ALICE

Harder



- 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

•Similarly to ATLAS measurement, model uncertainties (Herwig vs PYTHIA in the response and matching purity/efficiency

ALICE-PUBLIC-2021-002.







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



*E*_{radiator}=energy of the splitting prong at each declustering step

Cunqueiro, Ploskon, Phys.Rev.D 99 (2019) 7, 074027

- •Iteratively decluster jets with a fully reconstructed D⁰ among its constituents
- •Follow always the prong containing the D⁰
- •Register the splitting energy $E_{radiator}$ and the splitting k_T at each step

Define:

$$R(\theta) = \frac{1}{N^{D^0 \text{ jets}}} \frac{\mathrm{d}n^{D^0 \text{ jets}}}{\mathrm{d}\ln(1/\theta)} \Big/ \frac{1}{N^{\text{inclusive jets}}} \frac{\mathrm{d}n^{\text{inclusive jets}}}{\mathrm{d}\ln(1/\theta)} \Big|_{k_{\mathrm{T}}, E_{\mathrm{Radiator}}}$$

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





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

ALICE, arXiv:2106.05713



- Suppression of emissions at low angles for D⁰ jets as compared to inclusive jets
- Smaller effects for higher splitting energy

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

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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:

(Recursive SD) Dreyer et al, JHEP 06 (2018) 093

•New: Dynamical Grooming

1.Select the hardest branch in the C/A sequence 2.Drop all branches at larger angles

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

New at LHCP

The groomed momentum balance

Low z_g affected by non pert. effects (UE) More soft subleading prongs at large R

Good description by MC generators Largest discrepancies in the regions most affected by non pert. effects (higher β , low z_g)

 z_g exposes the QCD splitting function

Larkoski et al, Phys. Rev. Lett. 119, 132003 (2017)

The groomed jet radius

Low *p*_T, *R*=0.4 High p_{T} , large R=0.8, more grooming $\frac{dN}{d\theta_g}$ ALICE Preliminary ALICE pp β=0 pp $\sqrt{s} = 5.02 \text{ TeV}$ (1 / σ) d σ / d log₁₀(r_g) 3.5 N_{jets}, inc 3 ATLAS ALICE pp β=1 Charged jets anti-k_T ALICE pp $\beta=2$ √s= 13 TeV, 32.9 fb⁻¹ - $R = 0.4 |\eta_{iot}| < 0.5 Z_{cut} = 0.1$ Sys. uncertainty 2.5 Calorimeter-based, anti-k R = 0.8 PYTHIA8 Monash2013 $60.0 < p_{T, ch jet} < 80.0 \text{ GeV/}c$ Soft Drop, $z_{cut} = 0.1$, $\beta = 0$ 2.5 $p_{-}^{lead} > 300 \text{ GeV}$ 2 1.5⊟ 1.5 0.5 0.5 Ratio to Data 1.5 Data PYTHIA 0.5 -1.2 -0.8 0[,] 0.2 0.6 0.8 0.4 θ_{g} ALI-PREL-32834

Good description by MC generators

argest discrepancies with less grooming in the regions most affected by non-perturbative effects (collinear splits) See <u>talk of James Mulligan</u> for observables that measure the angle between jet axes found with different

recombination schemes (see also backup)

Dynamical grooming

- First measurement of dynamical grooming
- Good agreement between PYTHIA and data
- At high $k_{\rm T}$, different dyn grooming settings seem to select the same splitting

New at LHCP

First comparisons to analytical calculations at LO+N2DL accuracy <u>Caucal et al, arXiv:2103.06566</u>

Dynamical grooming

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New at LHCP

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The groomed jet mass: precision QCD

- See also CMS comparisons of groomed and ungroomed mass <u>CMS, JHEP 11 (2018) 113</u>
- Rg comparison to NLL calculations also available (see backup)

• The calculations are able to describe the data in the resummation regime at the level of 10%

Quark and gluon fragmentation

See talk by Markus Seidel

Z+jet, quark-enriched

- At LO, LHA, Width, Thrust, Multiplicity, are expected to be higher in gluon-enriched samples

New at LHCP

dijets, gluon-enriched

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

Quark fragmentation with LHCb

<u>See talk by Martin Kucharczyk</u>

New at LHCP

Z

Heavy flavour jet substructure

- than inclusive jets
- R_g consistent with inclusive jets: less sensitivity to small angles compared to full declustering
- and mass effects

ALICE-PUBLIC-2020-002

• Groomed momentum imbalance more asymmetric for D⁰-tagged jets, consistent with a harder fragmentation

• Fewer (SD) emissions in the D⁰-tagged jets measured via the n_{SD} (or n_{LH}), consequence of both color factors

Correlation of substructure observables

CMS Simulation

35.9 fb⁻¹ (13 TeV)

$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	+27 +100 +88 +64 +63 +63 +36	+100 +86 +27 +35 +34 +44 -23 -22 -19 -11 +25 +29
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	+100 +88 +64 +63 +36 +36	+27 +35 +34 +44 -23 -22 -19 -11 +25 +29
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	+88 +64 +63 +36 +46	+34 +44 -23 -22 -19 -11 +25 +29
$ M_{2}^{(2)} + 43 = \frac{1}{10} + 53 + 52 + 54 + 34 + 34 + 34 + 24 + 14 + 26 + 43 + 48 + 35 + 27 + 62 + 72 + 65 + 52 + 37 + 63 + 67 + 55 + 42 + 35 + 52 + 53 + 46 + 44 + 41 + 92 + 100 + 100 + 100 + 100 + 100 + 100 + 100 + 100 + 100 + 100 + 100 + 100 + 100 + 100 + 100 + 100 + 100 + 100 + $	+64 +63 +36 +46	-23 -22 -19 -11 +25 +29
M $_{2}^{(1)}$ +64 -69 +51 +68 +32 -35 +1 +22 +63 +63 +55 +48 +83 +83 +68 +51 +35 +85 +81 +64 +48 +39 +74 +70 +59 +52 +45 +100 +92 +7	+63 +36 +46	-19 -11 +25 +29
	+36 +46	+25 +29
C ⁽²⁾ ₃ +55 -20 +58 +54 +56 -23 +2 +45 +48 +29 +52 +47 +38 +59 +64 +65 +64 +49 +73 +79 +79 +76 +53 +73 +84 +93 +100 +45 +41 +4	+46	
C ₃ ⁽¹⁾ +58 -24 +59 +57 +55 -27 -0 +45 +55 +41 +64 +52 +45 +65 +68 +67 +64 +58 +82 +88 +88 +85 +64 +85 +96 +100 +93 +52 +44 +5		+33 +35
C ^(0.5) ₃ +63 -31 +59 +60 +53 -25 -2 +44 +60 +47 +70 +57 +55 +70 +70 +67 +62 +69 +89 +91 +87 +79 +75 +94 +100 +96 +84 +59 +46 +60	+45	+34 +33
C ^(0,2) ₃ +75 -44 +53 +59 +45 -24 -2 +37 +67 +52 +77 +70 +70 +70 +75 +67 +59 +51 +86 +93 +83 +72 +62 +92 +100 +94 +85 +73 +70 +53 +60 +94 +85 +73 +70 +53 +60 +94 +85 +73 +70 +53 +60 +94 +85 +73 +70 +53 +60 +94 +85 +73 +70 +53 +60 +94 +85 +73 +70 +53 +60 +94 +85 +73 +70 +53 +60 +94 +85 +73 +70 +53 +60 +94 +85 +73 +70 +53 +60 +94 +85 +73 +70 +53 +60 +94 +85 +73 +70 +53 +60 +94 +85 +73 +70 +53 +60 +94 +85 +73 +70 +53 +60 +94 +85 +73 +70 +70 +70 +70 +70 +70 +70 +70 +70 +70	+44	+30 +29
C ₃ ⁽⁰⁾ +81 -51 +34 +46 +25 -23 -2 +18 +71 +53 +78 +78 +78 +68 +50 +37 +28 +95 +83 +59 +44 +37 +100 +92 +75 +64 +53 +74 +52 +64	+42	+23 +26
C ₂ ⁽²⁾ +40 -14 +50 +46 +48 -27 -10 +39 +47 +47 +37 +28 +31 +50 +57 +60 +60 +41 +63 +80 +92 +100 +37 +62 +79 +85 +76 +39 +35 +50	+51	+24 +25
C ⁽¹⁾ ₂ +45 -24 +66 +62 +62 -19 -10 +55 +48 +49 +37 +28 +41 +65 +74 +76 +74 +51 +79 +95 +100 +92 +44 +72 +87 +88 +79 +48 +42 +50	+43	+20 +17
C ₂ ^(0.5) +55 -39 +73 +74 +66 -17 -8 +61 +55 +51 +45 +36 +58 +80 +84 +82 +75 +68 +92 +100 +95 +80 +59 +83 +91 +88 +79 +64 +55 +51	+42	+13 +8
C ^(0,2) ₂ +70 -56 +66 +74 +54 -19 -5 +48 +67 +59 +61 +54 +78 +88 +81 +71 +61 +90 +100 +92 +79 +63 +83 +93 +89 +82 +73 +81 +67 +70	+48	+7 +4
C ₂ ⁽⁰⁾ +79 -63 +41 +56 +28 -21 -3 +21 +74 +63 +71 +70 +88 +79 +60 +43 +31 +100 +90 +68 +51 +41 +95 +86 +69 +58 +49 +85 +63 +79	+52	+2 +9
C ₁ ⁽²⁾ +22 -34 +93 +81 +95 +4 +11 +84 +15 +0 +11 +12 +32 +65 +86 +96 +100 +31 +61 +75 +74 +60 +28 +51 +62 +64 +64 +35 +37 +7	-1	-16 -22
C ₁ ⁽¹⁾ +31 -47 +97 +92 +91 -1 +12 +84 +25 +8 +17 +16 +47 +80 +96 +100 +96 +43 +71 +82 +76 +60 +37 +59 +67 +67 +65 +51 +52 +1	+8	-23 -27
C ^(0.5) ₁ +45 -62 +94 +96 +81 -6 +11 +76 +41 +20 +27 +24 +67 +93 +100 +96 +86 +60 +81 +84 +74 +57 +50 +67 +70 +68 +64 +68 +65 +33	+19	-28 -29
C ^(0,2) ₁ +61 -78 +78 +91 +61 -12 +10 +55 +60 +37 +43 +39 +90 +100 +93 +80 +65 +79 +88 +80 +65 +50 +68 +75 +70 +65 +59 +83 +72 +5	+32	-29 -24
C ⁽⁰⁾ ₁ +71 -83 +47 +67 +30 -16 +6 +18 +71 +52 +56 +54 +100 +90 +67 +47 +32 +88 +78 +58 +41 +31 +78 +70 +55 +45 +38 +83 +62 +60	+41	-20 -7
τ ₄₃ +73 -28 +14 +21 +10 -17 +1 +2 +62 +36 +68 +100 +54 +39 +24 +16 +12 +70 +54 +36 +28 +28 +78 +70 +57 +52 +47 +48 +27 +50	+35	+23 +30
τ ₃₂ +69 -29 +13 +22 +8 -23 -1 -2 +67 +49 +100 +68 +56 +43 +27 +17 +11 +71 +61 +45 +37 +37 +78 +77 +70 +64 +52 +55 +35 +60	+48	+45 +50
τ ₂₁ +53 -29 +2 +14 -7 -49 -35 -14 +64 +100 +49 +36 +52 +37 +20 +8 +0 +63 +59 +51 +49 +47 +53 +52 +47 +41 +29 +63 +48 +8	+74	+34 +43
n _{SD} +81 -41 +20 +36 +8 -31 -19 -0 +100 +64 +67 +62 +71 +60 +41 +25 +15 +74 +67 +55 +48 +47 +71 +67 +60 +55 +48 +63 +43 +73	+59	+25 +34
ΔR_{g} +7 -26 +79 +69 +79 +12 -12 +100 -0 -14 -2 +2 +18 +55 +76 +84 +84 +21 +48 +61 +55 +39 +18 +37 +44 +45 +45 +22 +26 -10 +10 +10 +10 +10 +10 +10 +10 +10 +10 +	-17	-24 -33
Z _g -4 -20 +22 +22 +20 +18 +100 -12 -19 -35 -1 +1 +6 +10 +11 +12 +11 -3 -5 -8 -10 -10 -2 -2 -2 -0 +2 +1 +1 -1	-17	-18 -14
E -20 +8 +4 -3 +10 +100 +18 +12 -31 -49 -23 -17 -16 -12 -6 -1 +4 -21 -19 -17 -19 -27 -23 -24 -25 -27 -23 -35 -42 -5	-74	-12 -16
λ_2^{+} (thrust) +18 -35 +95 +82 +100 +10 +20 +79 +8 -7 +8 +10 +30 +61 +81 +91 +95 +28 +54 +66 +62 +48 +25 +45 +53 +55 +56 +32 +34 +20 +10 +10 +10 +10 +10 +10 +10 +10 +10 +1	-6	-20 -24
$\lambda_{0.5}^{+}$ (LHA) +39 -70 +95 +100 +82 -3 +22 +69 +36 +14 +22 +21 +67 +91 +96 +92 +81 +56 +74 +74 +62 +46 +46 +59 +60 +57 +54 +68 +64 +22 +21 +67 +91 +96 +92 +81 +56 +74 +74 +62 +46 +46 +59 +60 +57 +54 +68 +64 +22 +21 +67 +91 +96 +92 +81 +56 +74 +74 +62 +46 +46 +59 +60 +57 +54 +68 +64 +22 +21 +67 +91 +96 +92 +81 +56 +74 +74 +62 +46 +46 +59 +60 +57 +54 +68 +64 +22 +21 +67 +91 +96 +92 +81 +56 +74 +74 +62 +46 +46 +59 +60 +57 +54 +68 +64 +22 +21 +67 +91 +96 +92 +81 +56 +74 +74 +62 +46 +46 +59 +60 +57 +54 +68 +64 +22 +21 +67 +91 +96 +92 +81 +56 +74 +74 +62 +46 +46 +59 +60 +57 +54 +68 +64 +22 +21 +67 +91 +96 +92 +81 +56 +74 +74 +62 +46 +46 +59 +60 +57 +54 +68 +64 +22 +21 +67 +91 +96 +92 +21 +67 +91 +96 +92 +81 +56 +74 +74 +62 +46 +46 +59 +60 +57 +54 +68 +64 +22 +21 +67 +91 +96 +92 +81 +56 +74 +74 +62 +46 +59 +60 +57 +54 +68 +64 +22 +21 +67 +91 +96 +92 +81 +56 +74 +74 +62 +46 +59 +60 +57 +54 +68 +64 +22 +21 +10 +10 +10 +10 +10 +10 +10 +10 +10 +1	+14	-36 -34
λ_1^1 (width) +28 -52 +100 +95 +95 +4 +22 +79 +20 +2 +13 +14 +47 +78 +94 +97 +93 +41 +66 +73 +66 +50 +34 +53 +59 +59 +58 +51 +52 +13 +14 +47 +78 +94 +97 +93 +41 +66 +73 +66 +50 +34 +53 +59 +59 +58 +51 +52 +13 +14 +47 +78 +94 +97 +93 +41 +66 +73 +66 +50 +34 +53 +59 +59 +58 +51 +52 +13 +14 +47 +78 +94 +97 +93 +41 +66 +73 +66 +50 +34 +53 +59 +59 +58 +51 +52 +13 +14 +47 +78 +94 +97 +93 +41 +66 +73 +66 +50 +34 +53 +59 +59 +58 +51 +52 +13 +14 +47 +78 +94 +97 +93 +41 +66 +73 +66 +50 +34 +53 +59 +59 +58 +51 +52 +13 +14 +47 +78 +94 +97 +93 +41 +66 +73 +66 +73 +66 +73 +66 +73 +66 +73 +66 +73 +66 +73 +51 +52 +13 +14 +17 +78 +94 +97 +93 +14 +17 +78 +94 +97 +93 +14 +16 +73 +66 +73 +50 +34 +53 +59 +59 +58 +51 +52 +13 +14 +17 +78 +94 +97 +93 +14 +17 +78 +94 +97 +93 +14 +16 +73 +16 +73 +16 +17 +178 +10 +100 +178 +100 +178 +100 +178 +1188 +100 +178 +100 +178 +100 +178 +178 +100 +100 +100 +100 +100 +100 +100 +10	+4	-29 -32
λ_0^{2*} (p _T D*) -37 +100 -52 -70 -35 +8 -20 -26 -41 -29 -29 -28 -83 -78 -62 -47 -34 -63 -56 -39 -24 -14 -51 -44 -31 -24 -20 -69 -55 -34 -34 -34 -34 -34 -34 -34 -34 -34 -34	-16	+44 +32
λ_0^- (N) +100 -37 +28 +39 +18 -20 -4 +7 +81 +53 +69 +73 +71 +61 +45 +31 +22 +79 +70 +55 +45 +40 +81 +75 +63 +58 +55 +64 +43 +60 +100 +100 +100 +100 +100 +100 +100	+48	+26 +32
$ \begin{array}{c} \mathbf{z} \\ \mathbf$	5 S N	N 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3

Correlation of substructure observables

- • 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 $\alpha_{S}(m_{Z})$

35.9 fb⁻¹ (13 TeV) **CMS** POWHEG+PYTHIA 8 bottom jets charged particles $\alpha_{\rm S}(m_{\rm Z}) = 0.115^{+0.015}_{-0.013}$ LO+LL, 2-loop CMW 1 0.12 0.13 0.14

Most of the considered substructure observables are strongly correlated

Useful to select a set of minimally correlated variables:

 R_g , z_g , multiplicity, ϵ

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

n pert. effects by to $lpha_S(m_{
m Z})$

CMS, Phys.Rev.D 98 (2018) 9, 092014

What about colour flow?

24

ATLAS, Eur. Phys. J. C 78 (2018) 847

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

the parton shower ->prominent example is the Lund Jet Plane

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

<u>Robin Newhouse</u>, <u>James Mulligan</u>, <u>Helena Pintos</u> and many other interesting results on event shapes, Martin Kucharczyk

- New techniques like grooming or the iterative declustering allow to isolate different physics effects and constrain
- Beyond utility for searches and constraining SM calculations, new techniques expose building blocks of QCD like
- Not discussed here, check out recent results on jet substructure in heavy-ion collisions in talks by *Laura Havener*, inclusive/multi-jet production and correlations, Z boson and jets and more in talks by Salim Cerci, Tibor Zenis,

BACKUP

Other relevant recent results

<u>CMS, HEP 12 (2020) 082</u>

ALICE, Phys. Rev. C 101, 034911 (2020)

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

Measuring the angle between different jet axes

See talk by James Mulligan

<u>Cal et al, JHEP 04 (2020) 211</u>

E-scheme – SD

• Strong correlation between SD and E-scheme axes

• More aggressive grooming (β =0) ->larger ΔR_{axis} for SD and E-scheme • Negligible dependence on grooming condition for WTA—E-scheme • Differences sensitive to soft radiation pattern

WTA –E-scheme

R_g compared to analytical calculations

NLL calculation by Kang et al JHEP 02, 054 (2020)

Hadronisation

The Lund plane, ALICE

