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Lesson 2 jet substructure

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GDR-QCD:HIC in the QCD phase diagram, Nantes 4th July 2022



Jet substructure

Jets play a central role at the LHC

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



Here:

- 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



Dreyer et al, JHEP 12 (2018) 064

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

QCD Splitting probability

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

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



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 $\frac{1}{N_{\text{jets}}} \frac{d^{\text{M}}N_{\text{emissions}}}{dln(R/\Delta R) dln(1/z)}$ $\sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1}$ p_{T.1} > 675 GeV Pythia 8.230-2.2.5 (AHADIC 1.80 < ln(1/z) < 2.08 erpa 2.2.5 (String) wia 7.1.3 (Ang. ord. erwig 7.1.3 (Dipole) Ratio to Data MC Model 0.5 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



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

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

<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

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

ALICE-PUBLIC-2021-002.





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

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





The groomed momentum balance



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recovers the 1/z universal dependence of the z-kernel in QCD

Thaler et al, Phys.Rev.Lett 119, 12003 (2017)



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)





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 √s = 5.02 TeV (1 / σ) d σ / d log₁₀(r_g) 3.5 N_{jets}, inc 3 ATLAS ALICE pp β=1 Charged jets anti- k_{τ} ALICE pp β=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-328341

Good description by MC generators Largest discrepancies with less grooming in the regions most affected by non-perturbative effects (collinear splits)







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

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

Dynamical grooming



- First measurement of dynamical grooming
- Good agreement between PYTHIA and data
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New at LHCP

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



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



Quark fractions can be enhanced by selecting Z/γ -jet events

Quark and gluon fragmentation

Z+jet, quark-enriched



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

dijets, gluon-enriched

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



Measuring the angle between different jet axes



<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



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?

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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)

The dead-cone effect in QCD

Gluon radiation by a particle of mass m and energy E is suppressed within a cone of angular size m/E around the emitter

$$\frac{\frac{dN_Q}{d\theta}}{\frac{dN_q}{d\theta}} \propto \frac{\theta^4}{(\theta^2 + \theta_0^2)^2} \qquad \theta_0 = \frac{m_Q}{E_Q}$$

Dokshitzer, V.A.Khoze and S.I.Troyan "On specific QCD properties of heavy quark fragmentation", J. Phys. G 17 (1991)

Parametric dependence of the dead cone effect



Battaglia et al, DELPHI-2004-037 CONF 712

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The dead-cone effect in QCD

Direct consequences of the dead cone:

- Restriction of hard gluons with small $k_{\rm T}$ —> reduction of emissions, FF peaked at larger z
- Lower intrajet multiplicities

Experimental challenges for a direct measurement

- The decays of the heavy flavour particles happen at similar angular scales and fill the dead cone
- \bullet which radiation is suppressed



Accurate determination of the dynamically evolving direction of the heavy-flavour particle relative to

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



- •Iteratively decluster jets with a fully reconstructed D or B meson among its constituents
- •Follow always the prong containing the heavy flavour hadron
- •At the deepest levels of the jet tree, splittings are at sufficiently small angles to be sensitive to quark mass

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

ucted D or B meson among its constituents flavour hadron s are at sufficiently small angles to be sensitive to



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 signal extraction



I-PREL-339764

D⁰ from **D**^{*} decays

$$\rho^{\mathrm{D}^{0}\mathrm{jet}} = \sum_{i} \frac{1}{\varepsilon_{\mathrm{i}}} (\rho(\theta, E)_{S}^{D^{0}\mathrm{jet candidate}} - \frac{A_{\mathrm{S}}}{A_{\mathrm{B}}} \rho(\theta, E)_{\mathrm{B}}^{D^{0}\mathrm{jet candidate}})$$

Invariant mass distribution of the K±, π ∓ in bins of p_{T,D} • Side-band subtraction procedure in 2D on Lund Maps • Correction by D⁰ reconstruction efficiency



The signal extraction



I-PREL-339764

$$\rho^{\mathrm{D}^{0}\mathrm{jet}} = \sum_{i} \frac{1}{\varepsilon_{\mathrm{i}}} (\rho(\theta, E)_{S}^{D^{0}\mathrm{jet candidate}} - \frac{A_{\mathrm{S}}}{A_{\mathrm{B}}} \rho(\theta, E)_{\mathrm{B}}^{D^{0}\mathrm{jet candidate}})$$

- experimental efficiencies 29

The emission maps of HF and inclusive jets

D jets (side-band subtracted)



ALI-PREL-339746

Our main observable is the ratio of projections onto the θ axis for D and inclusive jets

Inclusive jets



ALI-PREL-339786

The emission maps of HF and inclusive jets

D jets (side-band subtracted)



ALI-PREL-339746

Detector effects cancel out in the ratio

Inclusive jets



ALI-PREL-339786

The dead-cone effect, exposed

ALICE, Nature 605, 440-446 (2022)



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

$R(\theta) = \frac{1}{n^{\text{D}^0 \text{jets}}} \frac{\text{dn}^{\text{D}^0 \text{jets}}}{\text{dln}(1/\theta)} / \frac{1}{n^{\text{inclusive,jets}}} \frac{1}{n^{\text{inclusive,jets}}}$ dninclusive, jets $d\ln(1/\theta)$ $p_{\text{T,inclusive jet}}^{\text{ch,leading track}} \ge 2.8 \text{ GeV/}c$ $k_{\rm T} > \Lambda_{\rm QCD}$, $\Lambda_{\rm QCD} = 200 \; {\rm MeV}/c$ $|\eta_{1ab}| < 0.5$ θ (rad) 0.08 0.22 0.14 80.0 0.05 $20 < E_{\text{Badiator}} < 35 \text{ GeV}$ 2.5 1.5 2 2.5 3 $\ln(1/\theta)$

Probing the Q->Qg splitting!



The dead-cone effect, exposed

ALICE, Nature 605, 440-446 (2022)



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

 $R(\theta) = \frac{1}{n^{D^0 \text{jets}}} \frac{\mathrm{dn}^{D^0 \text{jets}}}{\mathrm{dln}(1/\theta)} / \frac{1}{n^{\text{inclusive,jets}}}$ dn^{inclusive,jets} $d\ln(1/\theta)$

 $p_{\text{T,inclusive jet}}^{\text{ch,leading track}} \ge 2.8 \text{ GeV/}c$

shaded regions are expected dead cone for charm mass of 1.275 GeV in each Erad bin

Probing the Q->Qg splitting!





The dead-cone effect, exposed

ALICE, Nature 605, 440-446 (2022)



- Suppression of emissions at low angles for D⁰ jets as compared to inclusive jets
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$R(\theta) = \frac{1}{n^{D^0 \text{jets}}} \frac{\mathrm{dn}^{D^0 \text{jets}}}{\mathrm{dln}(1/\theta)} / \frac{1}{n^{\text{inclusive,jets}}}$ dn^{inclusive,jets} $d\ln(1/\theta)$ $p_{\text{T,inclusive jet}}^{\text{ch,leading track}} \ge 2.8 \text{ GeV/}c$ $k_{\rm T} > \Lambda_{\rm QCD}$, $\Lambda_{\rm QCD} = 200 \; {\rm MeV}/c$ $|\eta_{1ab}| < 0.5$ θ (rad) 0.08 0.22 0.14 0.08 0.05 $20 < E_{\text{Radiator}} < 35 \text{ GeV}$ real baseline is the ratio of light quark to inclusive emissions and it is dictated by differences in quark and gluon fragmentation 2.5 1.5 2 2.5 3 $\ln(1/\theta)$

Probing the Q->Qg splitting!





HF jet substructure prospects



- Mass scan: access to fully reconstructed beauty and charmed hadrons
- Possibility to isolate mass effects by cancelling out color effects in B to D ratios, unambiguous baseline
- Ideal: full reconstruction of heavy flavour hadrons. If not, deal with decay prongs
- Very interesting scenario in PbPb where medium-induced radiation can fill the dead cone

Summary Lessons 1-2

Jet definitions allow us to access the parton kinematics

Modern algorithms used at colliders are IRC safe. Anti- k_T is used as default due to its resilience against soft background

New techniques like grooming or the iterative declustering allow to isolate different physics effects and constrain the parton shower ->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. This opens up a wide window of opportunities in the context of heavy ion collisions as we will see in the next lessons

