Measurements of untagged and HF-tagged inclusive jet distributions in proton-proton collisions by ALICE.

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Measurements of inclusive untagged and heavy-flavour tagged (HF) jets test our understanding of strong interactions.

Compared to hadrons, jets are:

- not sensitive to fragmentation functions
- under better perturbative control

HF jets allow to study:

- differences between quark and gluons fragmentation (at higher $p_T$)
- impact of quark mass (at lower $p_T$)

Ratio of pp spectra to NLO pQCD:

Brewer et al. [2108.13434]
Jet measurements in ALICE

**Jet** is defined by jet algorithm: usually anti-kt, parameter $R$. Various $R$ show different sensitivity to perturbative effects, hadronization and UE. Taking ratio of two $R$ is beneficial from both exp. and theory side (see backup for details).

All results corrected to particle-level using unfolding
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ALICE measures jets with $5 < p_{T,jet} < 140$ GeV/c

Two types of jets distinguished:

“charged”, i.e. using only charged constituents measured in ITS+TPC
better acceptance, preferred for substructure measurements

“full”, including also neutral particles from EMCAL
more direct comparison to theoretical calculations, possible high $p_T$ trigger
Charged jet production cross section, pp $\sqrt{s} = 13$ TeV

- **PYTHIA**: overestimates the cross section
- **POWHEG+PYTHIA**: good description above 10-20 GeV/c, below: large difference even 50-100%

arXiv:2202.01548
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$R$ – ratios

- Both PYTHIA and POWHEG+PY able to describe ratios at higher $p_T$
- Overestimation of cross section at low $p_T$ increases with $R$ \Rightarrow ratio underestimated
- For PYTHIA predictions: underlying event subtraction plays crucial role
- No significant dependence on collision energy (nor system) observed
- Universal behaviour: higher $p_T$ jets are more collimated
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ALICE

Anti-$k_T$, $|\eta_{\text{jet}}| < 0.3$

$p_{T,\text{track}} > 0.15$ GeV/c

$R=0.2 / R=0.4$

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$\sigma(R=0.2) / \sigma(R=0.4)$

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$|\eta_{\text{jet}}| < 0.3$

$p_{T,\text{track}} > 0.15$ GeV/c

$\sqrt{s_{\text{NN}}} = 5.02$ TeV (UE subt.)

$\sqrt{s} = 7$ TeV (UE subt.)

$\sqrt{s} = 13$ TeV (UE subt.)

$\sqrt{s} = 5.02$ TeV (UE subt.)
Full jets and analytical calculation

- **Full** jets, pp at $\sqrt{s} = 5$ TeV, $R$ down to 0.1
- Two theoretical calculations:
  - POWHEG+PYTHIA8 – event generator
  - NLO+NLL – **analytical calculation** + non-perturbative correction
    
    $NP\ corr. = \frac{\text{ratio of inclusive jet spectrum}}{\text{(PYTHIA hadron-level, MPI on) / (PYTHIA parton-lvl, MPI off)}}$

Both describe most of the data within uncertainties. Tension at low $p_T$ and small $R$ can arise from mismodelling of NP correction, which is large there.
Ratio of jet cross sections: HF to untagged jets

HF jets

untagged jets

ratio

for more see also:
charmed jets: Ravindra on this session
beauty jets: Pietro: Wed, WG4, 12:30

- HF fraction vs $p_T$: increase then flatten
- tension with POWHEG hvq prediction of $D^0$-tagged jet fraction at low $p_T$
- b-jet fraction is well described by POWHEG dijet

Note the difference in $p_{T,\text{ch jet}}$ ranges and NLO calculations interfaced via POWHEG
See backup for POWHEG hvq and dijet comparison with previous measurement at $\sqrt{s} = 7$ TeV

arXiv:2204.10167
Groomed observables

\[ z_g = \frac{p_T^{\text{subleading}}}{p_T^{\text{leading}} + p_T^{\text{subleading}}} \]
\[ \theta_g = \frac{R_g}{R} = \frac{\sqrt{\Delta y^2 + \Delta \phi^2}}{R} \]

**Aim of grooming:** reduce impact of hadronization and UE to provide direct link with QCD calculations \((z_g\) is Sudakov safe and \(\theta_g\) collinear-infrared safe)

**Procedure:** recluster the jet with Cambridge-Aachen algorithm (angular ordered) and unwind the jet clusterization. Then iteratively remove soft branches until grooming condition is met.

For soft-drop:

\[ z_i > z_{\text{cut}} \theta_i^\beta \]

**Soft drop removes wide-angle, soft radiation.**

larger \(\beta \leftrightarrow \) less grooming, particularly collinear
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- Jets groomed with smaller $\beta$ are more collimated
- $\theta_g$ compared with pQCD calculation: SCET (Soft-Collinear Effective Theory) framework incl. all order resummation of large logarithms
- Good agreement within uncertainties in the perturbative region
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arXiv:2204.10246
Substructure of charm jets

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

$$z_i > z_{\text{cut}}$$

$n_{SD}$ = number of splittings satisfying soft-drop condition

Compared to untagged jets, D$^0$-tagged jets have:

- **less symmetric splittings** ($z_g \approx 0.5$) – consistent with expected impact of mass on QCD splitting function [P. Ilten et al. PRD 96 (2017) 054019]

- **significantly fewer splittings satisfy grooming condition** (with high enough $p_T$)
  -> consistent w/ hardening of the fragmentation of charm quarks compared to light quarks due to presence of dead-cone (suppressed collinear splittings)
  (but difference in fragmentation of quarks and gluons also plays a role)
ALICE has rich and unique jet program:

- pQCD predictions tested via cross section and substructure measurements
- Impact of non-perturbative effects studied and mitigated by variation in $R$ and grooming techniques
- No strong tension with the calculations in their applicability region with current precision
- HF jet sector explored via production (charm and beauty) and jet substructure (charm) measurements
- ... and much more not included

Upgraded ALICE in Run3 targets:

- High precision measurements in HF sector
- Substructure measurements in beauty jets
- Further nuclear modification studies
Measurement at various $R$

- anti-kt parameter $R$ changes the relative strength of various effects on the jet transverse momentum:
  - perturbative (magnitude $\downarrow R$)
  - non-perturbative: hadronisation $\downarrow R$ and underlying event (UE) $\uparrow R$
- sensitive to radial distribution of particles inside jet

Dasgupta et al. JHEP 0802 (2008) 055
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Computing the ratio of two $R$ is beneficial from two perspectives:
  ➢ *experimentally*: many uncertainties cancel out
  ➢ *theoretically*: calculations are effectively one order higher: NLO becomes effectively NNLO

example from first ALICE jet paper, ratio much more conclusive than individual $R$: PLB 722 (2013) 262-272
D⁰-tagged jets cross section

D⁰ is reconstructed in hadronic channel: D⁰ → K⁻π⁺ using PID and topological cuts

- Hardening of the spectrum with $\sqrt{s}$ observed
- PYTHIA Monash overestimates the cross section, SoftQCD Mode 2 works better
- POWHEG describe the higher $p_T$ region, at lower $p_T$ data points are at the upper band
- Uncertainties in MC much larger than in data
in ratio plot (right) the inclusive jet cross section (denominator) uses POWHEG dijet in both cases
\[ R(\theta) \]

- \[ \theta \text{ (rad)} \]
- \[ \ln(1/\theta) \]

**D^0**

ALICE Preliminary

\[ 2 < p_{T,D} < 36 \text{ GeV/c} \]

charged jets, anti-\( k_T \), \( R=0.4 \)

\[ |n_{\text{coll}}| < 0.5 \]

side-band subtracted

**Inclusive**

ALICE Preliminary

\[ 5 < p_{T,\text{jet}} < 50 \text{ GeV/c} \]

charged jets, anti-\( k_T \), \( R=0.4 \)

\[ |n_{\text{coll}}| < 0.5 \]

\[ k_2 > \Lambda_{\text{QCD}}, \Lambda_{\text{QCD}} = 200 \text{ MeV/c} \]
Dead-cone effect

Dead-cone effect: suppression of radiation at small angles ($\theta < m/E$) relative to the direction of emitter. It is a fundamental feature of all gauge quantum field theories.

ALICE provides first evidence of dead-cone effect at hadronic collider:

- **significant suppression of small angle ($\text{large } \ln(1/\theta)$) radiation**
- as expected: effect strongest for low $E_{\text{radiator}}$, suppression threshold changes with $E_{\text{radiator}}$ (shaded area)
- outlook: with same measurement for beauty, could provide constraints for quark masses

![Reclustering steps and dead-cone effect diagram](image)