ALICE measurements of inclusive untagged and heavy flavor-tagged jets in pp, p-Pb and Pb-Pb collisions

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Jets

- **Jet** - collimated spray of particles, created during fragmentation of quark or gluon after hard scattering
- Defined via IRC safe algorithms (anti-$k_T$, Cambridge/Aachen, $k_T$)
- Well understood theoretically in pQCD for pp collisions
- **Heavy Flavour** jets are initiated by a heavy quark ($m_q > \Lambda_{QCD}$) → perturbative production down to low jet $p_T$
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**p-p**
Test of the pQCD predictions
Reference for p-Pb and Pb-Pb

**p-Pb**
Study of the cold nuclear matter effects (CNM) nPDFs, Cronin effect, ...

**Pb-Pb**
In-medium energy loss: jet quenching for quark and gluon jets
Jets in ALICE

**EMCal:**
- Triggering on high-\(p_T\) \(\gamma, e^{\pm}\), and jets

**Time Projection Chamber:**
- Space-time points for tracking
- Particle identification via \(dE/dx\)

**Inner Tracking System:**
- Space-time points for tracking
- Primary and secondary vertex reconstruction

**Tracking and EMCal acceptance:**
- \(|\eta_{\text{track}}| < 0.9\)
- Tracking in full azimuth
- \(p_{T, \text{track}} > 0.15\, \text{GeV}/c\)
- \(|\eta_{\text{EMCal}}| < 0.7, \, \varphi < 110^\circ\)

**Jet reconstruction:**
- anti-\(k_T\) charged particle jet
- \(R = 0.2–0.6\)
- \(|\eta_{\text{jet}}| < 0.9 - R\)

**VZERO:**
- scintillator arrays at forward and backward \(\eta\)
- triggering

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Overview

1) Production of b-jets in pp and p-Pb @ $\sqrt{s_{NN}} = 5.02$ TeV

2) Radial profile of $D^0$ and $\Lambda_c^+$ hadrons in jets in pp @ $\sqrt{s} = 13$ TeV

3) Substructure of $D^0$-tagged jets and dead-cone measurement in pp @ $\sqrt{s} = 13$ TeV

4) Subjet fragmentation in pp and Pb-Pb @ $\sqrt{s_{NN}} = 5$ TeV
Methods to tag b-jets

Two independent methods were used for b-jet tagging:

1) Impact parameter - distance of closest approach of jet constituents to primary vertex
2) Secondary vertex (SV) - properties of the most displaced 3-prong secondary vertex

- Minimal significance of the SV displacement: \( SL_{xy} = \frac{L_{xy}}{\sigma_{Lxy}} \)
  - \( L_{xy} \) – distance between primary and secondary vertices
  - \( \sigma_{Lxy} \) – uncertainty of \( L_{xy} \) measurement

- Upper limit on the SV resolution: \( \sigma_{sv} = \sqrt{\sum_{i=1}^{3} d_i^2} \)
  - \( d_i \) – distance of closest approach of \( i \)-th prong to the SV

Default SV cut: \( \sigma_{sv} < 0.03 \text{ cm, } \frac{L_{xy}}{\sigma_{Lxy}} > 7 \)
b-jets in minimum bias pp and p-Pb collisions

The measured b-jet production cross section reproduced with POWHEG+PYTHIA

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b-jet fraction in pp and $R_{pPb}$

The measured b-jet fraction is compatible with the POWHEG prediction.

**Nuclear modification factor** compares particle yield measured in p-Pb with the yield from the corresponding number of independent pp collisions:

$$R_{pPb}^{b_jets} = \frac{1}{A} \frac{d\sigma_{pPb}^{b_jets}}{d p_{T, ch jet}} \frac{d\sigma_{pp}^{b_jets}}{d p_{T, ch jet}}$$

where $A$ is the number of nucleons in the Pb nucleus.

CNM effects in p–Pb smaller than current resolution

CMS measured full anti-$k_T$ $R = 0.3$ b-jets with $-2.5 < \eta_{jet} < 1.5$

Comparison of radial profile of $D^0$ and $\Lambda_c^+$ in jets in pp

Distribution of the radial distance between the hadron and the jet axis

$$r = \sqrt{(\phi_{\text{jet}} - \phi_{\text{HF}})^2 + (\eta_{\text{jet}} - \eta_{\text{HF}})^2}$$

$\phi_{\text{jet}}, \phi_{\text{HF}}$ - azimuthal angles of jet and HF hadron

$\eta_{\text{jet}}, \eta_{\text{HF}}$ - pseudorapidity of jet and HF hadron

- $\Lambda_c^+$ produced closer to the jet axis than $D^0$

- PYTHIA 8 Monash tune describes results better than PYTHIA 8 SoftQCD with color reconnection
Substructure of groomed $D^0$-jets and untagged jets in $pp$

Study jet shower via unwinding history of the clusterization process

Soft radiation at large angles is groomed away from jet shower with **Soft Drop** (SD) condition:

$$z < z_{\text{cut}} \theta^\beta$$

Momentum fraction of subleading prong:

$$z_g \equiv \frac{p_T, \text{subleading}}{p_T, \text{subleading} + p_T, \text{leading}}$$

**D$^0$-jets** exhibit larger $p_T$ asymmetry in comparison to **untagged jets**.
Substructure of groomed $D^0$-jets and untagged jets in pp

Angular distance $R_g$

$D^0$-jets and untagged jets consistent within uncertainties

$$\theta_g \equiv \frac{\sqrt{\Delta y^2 + \Delta \varphi^2}}{R} \quad \rightarrow \text{jet resolution parameter}$$

Number of splittings satisfying SD

Fewer splittings passed SD condition in $D^0$-jets than in untagged jets.

Result of harder fragmentation of the charm quark
- difference between quark and gluon jets
- dead-cone effect
Manifestation of the dead-cone effect for $D^0$-tagged jets

**Dead-cone effect:** suppression of gluon emission phase space for $\theta < \theta_{DC} = m_q / E_q \rightarrow$ mass effects at low $p_T$

$$R(\theta) = \frac{1}{N_{D^0\text{jets}}} \frac{d n_{D^0\text{jets}}}{d \ln (1/\theta)} / \frac{1}{N_{\text{untagged jets}}} \frac{d n_{\text{untagged jets}}}{d \ln (1/\theta)}$$

Ratio of the splitting-angle population for $D^0$-tagged jets to untagged jets

- Significant suppression at small-$\theta$
- Dead cone closing with increasing $E_{\text{radiator}}$
- First direct observation in pp

arXiv:2106.05713
Subjet fragmentation in pp and central Pb-Pb collisions

Constituents of inclusive jet with radius $R$ reclustered with anti-$k_T$ algorithm to a subjet with radius $r < R$.

Subjet measurements:

- Jet quenching effect for q jets vs g jets
- Test of universality of jet fragmentation function $\text{parton} \rightarrow \text{hadron}$ vs $\text{parton} \rightarrow \text{subjet}$

$$z_r = \frac{p_T^{\text{ch subjet}}}{p_T^{\text{ch jet}}}$$

PYTHIA8 pp $\sqrt{s} = 5$ TeV

Quark or gluon fraction

J. Mulligan EPS-HEP 2020
Subjet fragmentation in pp and central Pb-Pb collisions

- **Intermediate** $z_r$:
  - Gluon suppression $\rightarrow$ larger $z_r$
  - Soft radiation $\rightarrow$ smaller $z_r$

- **Large** $z_r$: region depleted by soft medium induced with gluon emission $\rightarrow$ purely quark jets

First subjet fragmentation measurement in QGP medium
Summary

- Heavy-flavor jet tagging extends accessibility of perturbative QCD regime to low jet $p_T$
- The ALICE measurement of charged b-jet $R_{ppb}$ at $\sqrt{s_{NN}} = 5$ TeV is compatible with unity
- Dead-cone effect is observed in pp collisions and it is seen to affect jet substructure
- Subjet fragmentation functions in Pb-Pb are affected by jet quenching

Outlook:

- Run3 will start next year
- New Inner Tracking System → improved capability for the HF tracking
- ALICE ready to take 100x larger luminosity w.r.t. Run 1 + Run 2