Exploring jet sub-structure in Pb-Pb and pp collisions with jet shapes in ALICE

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High-$p_T$ and virtuality partons are produced in initial hard scatterings:
- virtuality evolution through parton shower,
- hadronisation at $\Lambda_{QCD}$ scale.
Introduction: Jets in hadron collisions

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- In pp collisions:
  - calculable probes using pQCD,
  - allow to study hadronisation and underlying event effects.
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Hard partons traverse the QGP and lose energy while passing through it: “Gluon-bremsstrahlung effect”

Via the **parton interactions with the medium**, jets can be used to:
- study possible **modified fragmentation** with respect to the “vacuum” case (pp collisions),
- probe jet and medium properties.
Jet reconstruction in ALICE

$|\eta| < 0.9$, $0 < \phi < 2\pi$

ITS: Inner Tracking System (silicon)

TPC: Time Projection Chamber

Track $p_T > 150$ MeV/c

**Charged constituent jets ($jet^{ch}$)**
Jet reconstruction in ALICE

EMCAL: Pb scintillator sampling calorimeter
$|\eta| < 0.7$, $1.4 < \phi < \pi$
$\Delta \eta = \Delta \phi \approx 0.014$
Cluster $E_T > 300$ MeV

Neutral constituent jets

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Neutral constituent jets

Full jet reconstruction
matching the neutral and charged constituents

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ALICE jet results in pp collisions at $\sqrt{s} = 2.76$ and 7 TeV
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Better agreement for both the spectra and the jet profile if hadronization effects are taken into account in the calculations.
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Recent calculation based on NNLO+LL including UE and hadronization effects seems to be in better agreement than just NNLO calculations.


M. Dasgupta et al. JHEP 1606 (2016) 057
Jet shape definitions

- **Jet shapes** are observables constructed combining informations on how the variables of the constituents are distributed within the jet.

- Jet shapes can provide information about:
  - *parton-to-jet* fragmentation processes
  - *intra-jet distributions* (broadening, collimation)
  - possible *quark/gluon jet* differences
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- **Momentum dispersion** ($p_T D$):
  - Measures the momentum redistribution of jet constituents.
  - Jets with fewer constituents have higher $p_T D$.
  - Different $p_T D$ expected for **quark/gluon** jets due to the different fragmentation

\[
p_T D = \frac{\sqrt{\sum_i p_{T,i}^2}}{\sum_i p_{T,i}}
\]
Jet shape definitions

- **Momentum dispersion ($p_T D$):**
  - Measures the momentum re-distribution of jet constituents.

- **Radial moment ($g$):**
  - Measures the momentum re-distribution of jet constituents weighted by their distance from the jet axis.

\[
g = \sum_{i \in \text{jet}} \frac{p_T^i}{p_T^{\text{jet}}} |r_i|
\]

- large $g \rightarrow$ more broadened jets
- **gluon** jets have more likely large $g$
- smaller $g \rightarrow$ more collimated jets
- **quark** jets have more likely smaller $g$
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- **Transverse momentum difference of leading and subleading particles ($LeSub$):**
  - Transverse momentum difference of the hardest and second hardest constituents of the jet.
  - Jet shape not IRC safe but essentially background invariant, interesting for Pb-Pb collisions.

\[
LeSub = p_{T, \text{leading track}} - p_{T, \text{subleading track}}
\]
Charged jet shapes

Jet shapes, fully corrected to charged particle level.
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Reasonable agreement between data and PYTHIA calculations for all the jet shapes.

Use PYTHIA as reference for Pb-Pb

Important for low $R$ where hadronisation effects start to play an important role.
ALICE jet results in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
Jet reconstruction in heavy-ion collisions

- Heavy-ion collisions characterized by:
  - high multiplicity of low-$p_T$ particles
  - not related to hard scattering, coming mainly from soft medium interactions

- Jet background:
  - is dominant at low jet and jet constituent $p_T$
  - depends on the track multiplicity in the event
  - increases with $R^2$
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- Average background density \((\rho_{ch})\) estimated as:
  \[
  \rho_{ch} = \text{median}\left\{ \frac{p_{T,k\text{jet}}^{ch}}{A_{k\text{jet}}} \right\}
  \]
  - determined event-by-event.

- Correction applied to each jet in the event:
  \[
  p_T^{\text{jet}} = p_T^{\text{jet,rec}} - \rho \times A_{\text{jet,rec}}
  \]
Jet shapes background subtraction

- Average background removal for jet shapes based on recent techniques:
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  - Derivatives subtraction  
  - Constituent subtraction  
    - P. Berta et al, JHEP 1406 (2014) 092

- **PYTHIA detector level** jets embedded in Pb-Pb events.

![Graph showing dN/dg](image-url)
Jet shapes background subtraction

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- Subtraction methods (area based, constituent based) reduce the influence of the background on the shapes.
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- Residual difference between **PYTHIA detector level** jet shapes and **PYTHIA embedded subtracted** ones due to background fluctuations.

2D Bayesian Unfolding applied to remove background fluctuations and detector effects.
The **full jet** $R_{AA}$ shows a suppression also at high jet $p_T$ for $R=0.2$.

$$R_{AA} = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{d^2 N_{\text{ch, jet}}/dp_T d\eta|_{\text{Pb-Pb}}}{d^2 N_{\text{ch, jet}}/dp_T d\eta|_{\text{pp}}}$$
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Energy lost from the interaction of the parton within the medium not recovered within $R=0.3$.

$R_{AA}$ not precise enough to distinguish between the two models

JEWEL: C.Zapp et al. JHEP 1303 (2013) 080
Charged jet shapes

Focus on jet shapes to:
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- $p_T^{\text{D}}$ and $g$ distributions for $R=0.2$ jets are compatible with a more collimated and harder fragmentation in Pb-Pb than pp collisions.
Charged jet shapes

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- $p_T$D shifted to higher values in Pb-Pb collisions relative to PYTHIA Perugia11

- $g$ shifted to lower values in Pb-Pb collisions relative to PYTHIA Perugia11

- $LeSub$ in fair agreement with PYTHIA Perugia 11
The different fragmentation observed in Pb-Pb collisions for $R=0.2$ jets is qualitatively described by JEWEL model. C. Zapp et al., JHEP 1303 (2013) 080

- JEWEL collimates the jets since the soft particles are emitted at large angles.
- Results are in qualitative agreement for both $p_T D$ and $g$
Charged jet shapes: comparison with models

Qualitative comparison with quark/gluon jets at the same energy:
- gluon jets: quenched jets with intrajet broadening,
- quark jets: quenched jets without intrajet broadening.

Results seem to be closer to quark-like jet fragmentation.
Conclusions

- Jet shapes in pp collisions show a fair agreement with PYTHIA Tune Perugia 11
- More differential studies ($R, p_T^{jet}$) ongoing.
- Input from theory needed to compare with different MC (including hadronization, UE effects...)


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- Measurements of jet shapes in Pb-Pb collisions:
  - allow to **study modification of intra-jet particle distribution** by QGP
  - indicate that small $R$ jets ($R = 0.2$) are more collimated and fragment harder than PYTHIA pp reference.
  - indicate a **qualitative agreement with quark-like jet fragmentation** and are in agreement with JEWEL jet quenching model.
Back up slides
Reasonable agreement between data and MC calculations for all resolution parameters.

PYTHIA Perugia-2011 tends to better reproduce the results at high-$p_T^{\text{jet}}$.

HERWIG seems to be more in agreement in the low jet $p_T$ region.
ALICE jet results in Pb-Pb collisions

\[ R_{CP} = \frac{1}{\langle T_{AA} \rangle N_{evt}} \frac{1}{d^2 N_{ch\ jet}} \frac{d^2 N_{ch\ jet}}{dp_{T, ch\ jet} d\eta_{ch\ jet}} \bigg|_{central} \]

1. The **charged jet** \( R_{CP} \) shows a decreasing trend as a function of the collision centrality\(^(*)\) for \( R=0.3 \).

\(^{*}\)Centrality: quantity used to determine the overlap region of the two colliding nuclei. Events are classified in centrality classes in terms of the percentiles of the total A-A-A cross section.
Exploiting the h-jet coincidence measurement it is possible to suppress the combinatorial background effects and explore larger jet radii.

No significant medium-induced modification of intra-jet energy distribution for $R \leq 0.5$ is observed.
Jet shape distributions PYTHIA Perugia 11

ALICE Simulation
PYTHIA Perugia 11
pp √s = 7 TeV
Anti-kt charged jets, R = 0.2
40 < p_T^{jet,ch} < 60 GeV/c
√s dependence of jet shapes PYTHIA Perugia 11

Not negligible difference in the jet shapes due to due to q/g difference fraction at two collider energies.
Tracking efficiency. Variation of ±4% dominate the jet energy scale uncertainty.

Unfolding:
- Regularization: variations of ±3 iterations in the procedure.
- Truncation: difference to measured yield at a 10 GeV lower value than default one.
- Prior: Variation of 20% between $p_T^{\text{part}}$ and shape$^{\text{part}}$. Default value PYTHIA Perugia 0.
- Background subtraction: two different methods used to estimate the background.
If the jet would lose energy as a whole (single emitter) then we would expect Pb-Pb shapes to be in agreement with vacuum shape at higher-$p_T$.

The radial moment seems to show this behavior.

$p_TD$ does not, but it has a milder dependence on the transverse momentum.