Jet measurements in small systems relevant for medium modifications

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Outline

• Signatures and hard probes for quark-gluon plasma

• Observations in small size final states
  • Constraints on jet quenching based on latest measurements
  • Collective behavior in several systems
  • Dijet correlations and per-event yields
QGP medium with hard probes

- Quark Gluon Plasma (QGP): unique state of matter formed in heavy ion collisions
- Wide range of signatures in dense system
  - Suppression of jet spectra due to the energy loss in strongly interacting medium
  - Azimuthal anisotropies (collective flow)
- Smaller systems: benchmark for the interpretation of the heavy ion collision observations
  - Intermediate system: p-Pb collisions
  - Smallest: p-p collisions with high multiplicity

https://physics.aps.org/articles/v10/s139
https://www2.lbl.gov/Science-Articles/Archive/sslb/2008/feb-jets.html
https://physic.s.aps.org/articles/v10/1139
Jet suppression

- Modified particle $p_T$ spectrum due to energy loss, observables of interest:
  - Nuclear modification factor
  - Per-jet charged particle yield
- Significant difference between heavy-ion and small systems
- Jet quenching in nuclear modification factor measurements

**Measurements in Pb-Pb or p-Pb collisions**

$$R_{AA}(p_T) = \frac{dN^{AA}/dp_T}{\langle N_{coll}\rangle dN^{pp}/dp_T} = \frac{dN^{AA}/dp_T}{T_{AA} d\sigma^{pp}/dp_T}$$

Nr of binary NN collisions
p-p reference

No quenching in p-Pb collisions at $p_T > 2$ GeV

Clear sign of suppression in Pb-Pb events

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Clear sign of suppression in Pb-Pb events

R_{AA} < 1 suppression
Latest results from ATLAS

- Ratio between per-jet (jet $p_T > 60$ GeV) charged particle yields

\[
I_{pPb} = \frac{Y_{pPb}}{Y_{pp}}
\]

- Away-side hadrons from fragmentation $p_T \sim 60$ GeV

$\frac{p_T^{ch} > 1$ GeV compatible with $I_{pPb} \sim 1$

5% centrality independent enhancement at near side

Hint of depletion at $p_T < 1$ GeV
Jet quenching constraints

- Combined measurements with jet $p_T > 30$ GeV
- Focusing on the central collisions
- Similar trend for both sides
- Results are compared with Angantyr and AMPT (A MultiPhase Transport model) generator predictions
  - $p_T^{ch} > 4.5$ GeV: no UE subtraction is required
  - Running with or without final-state effects

Small near-side enhancement, also predicted by Angantyr

AMPT without final state interactions show good agreement

No sign of jet quenching in $z = p_T^{ch} / p_T^{jet} = 0.05$-1.0
Final state anisotropies

- Two-particle angular correlations in high-energy collisions

\[
\frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{assoc}}}{d(\Delta \eta) d(\Delta \phi)} = \frac{S(\Delta \eta, \Delta \phi)}{B(\Delta \eta, \Delta \phi)}
\]

Jet particle correlation function

- Short range collective effects observed in all systems

- Ridge structure: hint of long range correlations

- Random combinatorial background

- Associated particles

- Central Pb-Pb collisions

- Trigger particle

- p-p with high multiplicity

- Pb-p with high multiplicity
Elliptic flow determination

- Fourier expansion of the particle-pair projected azimuthal correlations
  \[ \frac{dN_{\text{pair}}}{d(\Delta \phi)} \propto 1 + 2 \sum v_{n\Delta} \cos(n \Delta \phi) \]

- Specific kinematic constraints on trigger and associated particle pairs

- Harmonics \((v_n)\) interpreted as flow observables
  - Measured vs trigger particle \(p_T\)
  - Low-\(p_T\) regime: UE-UE dominated
  - High-\(p_T\) : more HS-UE pairs

\(v_2\) increases up to 3 GeV, and decreases continuously as the jet physics regime is reached.

Significant difference between minimum bias and jet triggered events at intermediate \(p_T\): different HS-UE contribution.
ALICE results compared to AMPT

- $v_2 > 0$ without jet quenching in high multiplicity $p$-Pb?
- Inclusive charged particles show different trend
- AMPT predictions with string melting also included
  - All strings converted to $q$ and anti-$q$
  - Elastic scattering between these partons responsible for long-range correlations

\[ Q_{p\text{Pb}}(p_T; \text{cent}) = \frac{dN_{\text{Pb}}}{dN_{\text{coll}}} \left( \frac{N_{\text{Glauber}}}{dN_{pp}/dP_T} \right) \]

Initial spatial anisotropy \quad Partons escape more likely along the shorter axis of the volume \quad Azimuthal anisotropies not from hydrodynamic flow

Predicted $v_2 > 0$

$v_2$ for jet particles is below the model predictions

Modification factor described at high-$p_T$
Dijets in small systems

- Properties of dijets measured in photonuclear and p-Pb and p-p collisions
  - Angular correlations
  - Per-event dijet yields

Non-trivial angular correlations in γ-Pb dijet event

Central / peripheral dijet yield

Modifications in dijet yield vs pseudorapidity compared to p-p reference system (shadowing)

Q_t: vector sum of two jets
Overview

- Hard probes can be used to explore the behavior of small systems
- Long-range angular correlations observed in heavy ion, but also in high multiplicity p-Pb and p-p collisions
- Elliptic flow $v_2 > 0$ in various measurements as in heavy-ion collisions
  - But no sign of jet quenching
  - Latest results: string melting model (in AMPT) suggests positive $v_2$ without hydrodynamical flow effects
- Modifications in dijet yields, and unexpected angular correlations are measured in photonuclear and p-Pb collisions
- Run-3 heavy ion runs provide unique opportunity: O-O collisions (details in backup) and increased p-Pb luminosity
  - Further understanding of the initial state is expected
Backup
Jet quenching constraints from ATLAS measurements

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Oxygen run at the LHC

- Alternative intermediate system: O-O collisions
  - Broad covered final state multiplicity
  - Geometrically small system, but large fluctuations expected
  - Further investigation of the missing jet quenching
  - Flow effects can also be studied to explore the intermediate multiplicity range between p-p, p-Pb and Pb-Pb systems
- Short run is proposed at the LHC
  - 6.37 TeV cm energy with ~1 nb⁻¹ delivered data
Projections of the O-O run results

- Foreseen correlation measurements over large variety of final state multiplicities

Connection between the fluctuation dominant and the geometry dominant region

Statistical precision < 1.5% up to 50 GeV

- Search for energy loss measuring the nuclear modification factors

- The possibility of observing a reduction in $R_{AA}$ depends on the size of the effect

$20 < p_T < 25$ GeV

Uncertainties are the smallest for the predictions

$\text{Statistical precision } < 1.5\%$ up to 50 GeV
References

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