Investigating jet modification in heavy-ion collisions at $\sqrt{s_{NN}} = 5.02$ and 2.76 TeV with ALICE

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Quark-Gluon Plasma

- **Quark-Gluon Plasma (QGP)**
  - Hot & dense QCD matter
    - Similar to early Universe ~1μs old
  - Deconfined state of quarks and gluons
  - Theoretically inferred through lattice gauge simulations of QCD

- **Ultra-Relativistic Heavy Ion Collision**
  - High-energy nucleus-nucleus collisions at particle accelerators (RHIC, LHC)

- **Hard Probes**
  - Produced by high-$p_T$ QCD process
  - Initial hard parton scattering

- **Soft Probes**
  - Bulk of created particles
  - Dominant at low-$p_T$
Jet as Hard Probes of the QGP

Jet Quenching

- Partons' energy loss in the QGP
  - Energy attenuation/disappearance or shape modification of observed Jets
  - Evaluation of these modifications allows to assess QGP properties

1. **Auto-generated probes**
   - short QGP lifetime (\(\sim 10^{-23}\) s)

2. **Probe the entire medium evolution**
   - occur at early stage: \(\tau \sim 1/Q\)

3. **Well calibrated probes**
   - production rate calculable within pQCD

4. **Copious production at the LHC**

5. **Access to initial parton kinematics**
   - via jet reconstruction
Jet Measurement in LHC-ALICE

Charged Particles: $|\eta| < 0.9, \ 0 < \phi < 2\pi$
- **ITS**: Silicon tracking detector
- **TPC**: Time projection chamber

$\Rightarrow$ “Charged” Jet

Electromagnetic particles: $|\eta| < 0.7$
- **EMCAL**: (**DCAL**: Run 2 from 2015-)
- Pb-Scintillator sampling calorimeter
- **PHOS**: Lead-tungsten crystal (PWO) based calorimeter

$\Rightarrow$ Charged+EM = “Full” Jet
Main Physics Observables

Nuclear Modification Factor: $R_{AA}$

- Evaluate the jet suppression as compared to $pp$
- $R_{AA} < 1$
  - Jet (parton) energy loss due to parton interaction with the medium
  - Out-of-cone energy radiation

$$R_{AA} = \frac{dN^{AA}}{d\eta} / \frac{dN^{pp}}{d\eta} = \frac{dN^{AA}}{d\eta} / T_{AA} \frac{d\sigma^{pp}}{dp_T}$$

Cross Section Ratio

- Sensitive to structure of jets
- Jet broadening/collimation
Jet Production in $pp$ 5.02 TeV

- Measured charged jet cross sections are well described by POWHEG+Pythia8 (NLO pQCD + parton shower, hadronization)
  - for cross section and cross section ratio
- POWHEG+Pythia8 viable reference for Pb-Pb measurements where lack of $pp$ data
Inclusive Jet $R_{pA}$ at 5.02 TeV

- Is there jet quenching in p-Pb?
- Charged jet $R_{pA}$ in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV
- $R_{pA}$ is consistent with unity.
  - Jet production in p-Pb is well described by binary scaling of $pp$
  - No modification within uncertainties

![Plot showing $R_{pA}$ values for charged jets in p-Pb collisions at 5.02 TeV.](image)

Reference: Scaled pp jets 7 TeV

Global normalization uncertainty

Resolution parameter $R = 0.2$

Resolution parameter $R = 0.4$

ALICE p-Pb $\sqrt{s_{NN}} = 5.02$ TeV

Charged jets, anti-$k_T$, $|\eta_{lab}| < 0.5$

Jet Radial Structure in $p$-Pb 5.02 TeV

- Jet cross section ratio between different resolution parameters
  - $\sigma(R=0.2) / \sigma(R=0.4)$
- No indication of nuclear modification in jet radial profile
- $\Delta E < 0.4$ GeV/c medium-induced energy transport out of $R = 0.4$ cone.
  (arXiv:1712.05603)

![Graph showing jet radial structure in p-Pb 5.02 TeV]

Charged jets, anti-$k_T$

- ALICE p-Pb $\sqrt{s_{NN}} = 5.02$ TeV, $|\eta_{lab}| < 0.5$
- ALICE pp $\sqrt{s} = 7$ TeV, $|\eta_{lab}| < 0.3$
- NLO pQCD calculations 5.02 TeV (boosted)
  POWHEG+PYTHIA8 with CTEQ6.6+EPS09
- PYTHIA6 Perugia 2011 5.02 TeV

arXiv:1503.00681
Inclusive Jet $R_{AA}$ at 5.02 TeV

- Charged and Full Jet $R_{AA}$ in the most central Pb-Pb collisions
- $R_{AA}$ is smaller than unity
  - Strong jet suppression
  - Increase gently in low-$p_T$ and reach a constant value
- No significant difference between Full and Charged jet $R_{AA}$
Inclusive Jet $R_{AA}$ at 5.02 TeV

- Charged jet $R_{AA}$ in four centrality classes
- Larger $R_{AA}$ (smaller suppression) in the peripheral collisions, due to smaller system size.
- Jet $R_{AA}$ for different resolution parameter are consistent within systematic errors
  - Jet radial structure is similar to $pp$?

![Graph showing $R_{AA}$ for different pT and centrality classes.](image)
Jet Radial Structure in Pb-Pb 5.02 TeV

- Jet cross section ratio between different resolution parameters
  - $\sigma(R=0.2) / \sigma(R=0.3)$

- Consistent to POWHEG+Pythia8 and JEWEL expectation within uncertainties
  - The angular structure of jet core is unmodified in AA as compared to $pp$.
  - More precision needed to conclude
Introduction of Another Angle : Heavy-Flavor in Jets

- Charged Jet containing $D^0$ in its constituent
  - Suppression of charm quarks
  - Robust against combinatorial background
  - Enable to extend jet $p_T$ down to few GeV/c
- Strong D-tagged jet suppression in the most central Pb-Pb collisions

- Investigation of type/mass dependent parton energy loss mechanism is expected
  - Charm and beauty jets
  - Motivation for upcoming Run 3, 4 with more data/precision

see A.Rossi talk
(Heavy Ion 1, Jul. 5th)
ALICE successfully measured charged and full jet in $pp$, $p$-Pb and Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for jet resolution parameters of $R=0.2$ and 0.3

- Nuclear modification factor ($R_{pA}$, $R_{AA}$)
  - No jet suppression in $p$-Pb collisions
  - Strong jet suppression in the most central Pb-Pb collisions
    - Support significant jet energy loss via parton-medium interactions

- Jet cross section ratio between different $R$
  - Jet angular structure is consistent to $pp$ within uncertainties at the moment
  - More precision needed
    - Extend the range: larger $R$ and/or jet-$p_T$ reach

- Study of parton type dependent jet modification is starting
  - Strong suppression of D-tagged jet
  - Detail and/or extended study of heavy-flavor jets expected at Run3, 4
Thank you for your attention!
1. Event/Track Selection
- √s_{NN} = 5.02 TeV, Pb-Pb
- Min. Bias trigger (61M events)
- |v_{Z}| < 10 cm

2. Jet Reconstruction
- anti-\( k_T \) algorithm
- \( R = 0.2, 0.3 \)
- \(|\eta_{\text{jet}}| < 0.9 - R\)
- \( p_{T}^{\text{lead}} > 5 \text{ GeV/c} \)

3. Soft BKG subtraction
- subtract average BKG event-by-event

4. Unfolding
- correct detector effects
- correct BKG fluctuation

5. Inclusive Jet spectrum

Charged Particle
- |\eta| < 0.9
- \( p_{T} > 0.15 \text{ GeV/c} \)
- hybrid track selection

Average Background Density
- \( k_T \) algorithm
- median calculation

SVD unfolding method
- input response of detector effects and BKG fluctuation
Challenge in Heavy-Ion Collisions

- Large background contribution to jet energy
  - $dN_{\text{ch}}/d\eta \sim 1300$ (0-10% centrality)

- **Average Background Density** : $\rho$
  - $k_T$ clusters excluding two leading clusters
  - $\rho = \text{median} \left( \frac{p_{T,i}}{A_i} \right)$
  - event-by-event calculation
  - $\rho \sim 145 \text{ GeV/c}$ for 0-10%
  - (~18 GeV/c for $R=0.2$ jets)

- **Combinatorial Jets Removal**
  - random combination of BKG particles
  - minimum leading constituent $p_{T,\text{lead}} > 5 \text{ GeV/c}$ is required

ALICE Pb-Pb, $\sqrt{s_{NN}} = 5.02 \text{ TeV}$
$\mu_{T,\text{track}} > 0.15 \text{ GeV/c}$

Hiroki Yokoyama for the ALICE collaboration
Underlying Event Fluctuation

- **Background fluctuation : \( \delta p_T \)**
  - from region to region around average background
- **Random Cone method**
  - (exclude leading jet neighbour : \( \Delta r > 1.0 \))
  \[
  \delta p_T = \sum_{i}^{RC} p_{T,i}^{\text{track}} - \rho \pi R^2
  \]

- **\( \delta p_T \) width (magnitude of fluctuation)**
  - \( \sim 5 \text{ GeV/c} \) (0-10% , \( R=0.2 \))
  - smaller in peripheral
Jet Energy Resolution

- Jet energy resolution is derived by the Response Matrixes
- Effect from Underlying Event Fluctuation
  - dominant in lower jet $p_T$
- Detector Effect
  - dominant at higher jet $p_T$
Jet Reconstruction Algorithm

- FastJet anti-\(k_T\) algorithm (\(p=-1, p=1\) for \(k_T\) algorithm)
  - calculate \(d_{ij}\) and \(d_{iB}\) by all particles combination
    - when minimum “d” among them is part of \(d_{ij}\)
      - merge particle “i” and “j”
    - when minimum “d” among them is part of \(d_{iB}\)
      - that cluster defined as jet
  - repeat until no particle are left

\[
d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2},
\]
\[
d_{iB} = k_{ti}^{2p},
\]
\[
\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2
\]
Jet Reconstruction

- Combine/classify particles into clusters sequentially
  - based on $p_T$ weighted distance
  - (correspondence between parton level and detector level).
- Anti-$k_T$ algorithm
  - start clustering from high-$p_T$ particles $\Rightarrow$ Signal Jet in Heavy Ion collisions
  - Circular and centred around harder energy deposit (with radius $\sim R$)
- $k_T$ algorithm
  - start clustering from low-$p_T$ particles $\Rightarrow$ Estimation of Soft BKG
pp Inclusive Jet Cross Section

Jet cross section at $\sqrt{s} = 5.02$ TeV pp collisions in 2015

- POWHEG NLO calculations well describes measured spectrum within systematic uncertainties

Dataset

- $\sqrt{s} = 5.02$ TeV, pp collisions
- MB triggered events (25.5M events)

Charged track selection

- $|\eta| < 0.9$, $p_T^{\text{track}} > 0.15$ GeV/c

Jet reconstruction

- anti-kt jet reconstruction algorithm
- $R = 0.2$
- $|\eta| < 0.7$, ($p_T^{\text{lead}} > 5$ GeV/c for $R_{AA}$ ref.)

Unfolding

- to correct for detector effects
Pb-Pb Inclusive Charged Jet Cross Section

Jet cross section at $\sqrt{s_{NN}} = 5.02$ TeV PbPb collisions in 2015

Dataset
- $\sqrt{s} = 5.02$ TeV, PbPb collisions
- MB triggered events (68M events)
- 0-80% centrality

Charged track selection
- $|\eta| < 0.9$, $p_T^{\text{track}} > 0.15$ GeV/c

Jet reconstruction
- anti-kt jet reconstruction algorithm
- $R = 0.2, 0.3$
- $|\eta| < 0.9-R$, ($p_T^{\text{lead}} > 5$ GeV/c)
**Pb-Pb Inclusive Full Jet Cross Section**

- **Jet cross section at \( \sqrt{s_{NN}} = 5.02 \) TeV PbPb collisions in 2015

**Dataset**
- \( \sqrt{s} = 5.02 \) TeV, PbPb collisions
  - MB triggered events (4.5M events)
  - 0-10% centrality

**Charged track selection**
- \(| \eta | < 0.9, p_{T}\text{track} > 0.15 \) GeV/c

**EM cluster selection**
- \( E_{\text{clus}} > 0.3 \) GeV

**Jet reconstruction**
- anti-kt jet reconstruction algorithm
  - \( R = 0.2, 0.3 \)
  - \(| \eta | < 0.9 - R, (p_{T}\text{lead} > 5 \) GeV/c)