Transverse momentum spectra of single particles and jets in p-Pb collisions from ALICE at the LHC

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How do we measure?

Collide Pb-Pb and compare results to reference measurements in pp and p-Pb

Soft QCD and pQCD + fragmentation in vacuum. Reference for p-Pb and Pb-Pb.

Initial state effects (shadowing/gluon saturation). Final state effects? Reference for Pb-Pb.

Thermal production, collective flow, recombination, jet quenching and fragmentation in the quark-gluon plasma (QGP).
How do we measure?

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Today focus on p-Pb collisions.

LHC: \(\sqrt{s_{NN}}=5.02\) TeV: p (4 TeV) + Pb (1.58 TeV/u) → Rapidity shift \(\Delta y_{NN} = 0.465\) in the p-beam direction

Thermal production, collective flow, recombination, jet quenching and fragmentation in the quark-gluon plasma (QGP).
A Large Ion Collider Experiment

- Excellent particle identification capabilities in a large $p_T$ range 0.1-20 GeV/c
- Good momentum resolution $\sim$1-5% at $p_T = 0.1-50$ GeV/c

Central barrel tracking and PID $|\eta| < 0.9$

MUON arm $-4.0 < \eta < -2.5$
Selected results from p-Pb

**Single particle production**
- Charged particles
- Identified light-flavor hadrons

**Jets**
- Inclusive jet spectra
- Jet structure
CHARGED PARTICLES
Nuclear modification factor in p-Pb

\[ R_{pPb} = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{pPb}}{dp_T} / \frac{dN_{pp}}{dp_T} \]

\( R_{pPb} = 1 \iff \text{no modification} \)

No pp available at \( \sqrt{s}=5.02 \) TeV. pp reference determined using measurements at different \( \sqrt{s} \).

Particle production at high \( p_T > 8 \) GeV/c
- No modification for charged hadrons in p-Pb collisions (no centrality selection)
- No modification for weak bosons and photons in central Pb-Pb collisions
- Strong suppression of charged hadrons in central Pb-Pb collisions (\( R_{AA} < 0.5 \))

→ Suppression is due to final state effects in hot and dense QCD medium
Centrality selection in p-Pb is non trivial due to large fluctuations.

All centrality estimators used for p-Pb introduce bias on the measured $p_T$ spectra at mid-rapidity.

→ Impossible to define unbiased $R_{pPb}$ vs. centrality

Instead define biased $R_{pPb}$: $Q_{pPb}$ obtained using hybrid method

\[
Q_{pPb} = \frac{1}{\left\langle N_{cent}^{coll} \right\rangle} \frac{dN_{pPb}}{dp_T} / \frac{dN_{pp}}{dp_T}
\]
$Q_{pPb} - \text{hybrid method}$

$Q_{pPb} = \frac{1}{\left\langle N_{\text{coll}}^{\text{cent}} \right\rangle} \frac{dN_{pPb}/dp_T}{dN_{pp}/dp_T}$

$<N_{\text{coll}}>$ calculated using ZN centrality classes and particle production scaling properties at mid-rapidity:
- $N_{\text{ch}}$ on Pb-side scales as $N_{\text{part}}$:
  - $N_{\text{ch}}$ on Pb-side:
  - $N_{\text{ch}}$ scales as $N_{\text{part}}$:

ALICE, PRC 91, 064905 (2015)

No modification of high-$p_T$ particle production for all centralities: $Q_{pPb} \sim 1$

$\rightarrow$ Suppression seen in central Pb-Pb collisions is due to final state effects
IDENTIFIED LIGHT-FLAVOR HADRONS
Pion, kaon and proton $R_{pPb}$

→ Suppression in Pb-Pb collisions is due to final state effects!
Pion, kaon and proton spectra in multiplicity bins

- Harder spectra with increasing multiplicity and with increasing particle mass
- Flattening of proton spectra at low $p_T$ with increasing multiplicity $\rightarrow$ indication of flow
Comparison to models at low $p_T$

- **Blast-wave**
  - Hydro inspired model
  - Hard/soft scattering contribute to jet/bulk
  - Bulk matter described with hydro

- **Kraków**
  - Initial conditions from Glauber MC
  - Viscous hydrodynamic expansion
  - Statistical hadronization at freeze-out

- **EPOS LHC**
  - QCD-inspired model based on Gribov-Glauber approach
  - Reproduces $dN_{ch}/d\eta$ in NSD p-Pb

Hydro models reasonably well describe data in p-Pb → indication of flow
Blast-wave comparison of pp, p-Pb and Pb-Pb

- pp, p-Pb and Pb-Pb data in multiplicity bins
- pp PYTHIA8 MC in multiplicity bins

**Blast-wave** fit parameters:

- $T_{\text{kin}}$ – kinetic freeze-out temperature
- $\langle \beta_T \rangle$ - radial flow velocity

Similar evolution of the blast-wave parameters with increasing multiplicity

**PYTHIA8** pp (no hydrodynamic evolution) also shows the same trend

- Color reconnection causes similar effect as flow

Published p-Pb and Pb-Pb results: ALICE, PLB 728 (2014) 25
Baryon to meson ratio increases with multiplicity

- p-Pb: flow or color reconnection as in pp?
- Pb-Pb: flow and recombination
Jet measurement in ALICE

TPC+ITS: charged jets – only charged jet constituents
TPC+ITS+EMCAL: full jets – charged + neutral ($\pi^0$, $\gamma$)

Background fluctuations: ALICE, JHEP 053 (2012) 1203

Jet cone with radius R

$R^2 = \Delta \eta^2 + \Delta \phi^2$

Jet finder: anti-$k_t$ algorithm
Underlying Event (UE) background subtraction:

- Event wise ($k_t$ algorithm)
  $p_{T_{\text{jet}}} = p_{T_{\text{jet,rec}}} - \rho \cdot A_{\text{jet}}$

- Fluctuations on statistical level
  $\delta p_{T_{\text{jet}}} = (p_{T_{\text{jet,rec}}} - \rho \cdot A_{\text{jet}}) - p_{T_{\text{jet,true}}}$
Jet $R_{pPb}$ vs. $R_{AA}$

ALICE, arXiv:1503.00681

- Charged jet $R_{pPb}$ (no centrality selection)
- Reference: Scaled pp jets at 7 TeV
- Full jet $R_{AA}$ (0-10%, 10-30% centrality)
- Measured pp reference at 2.76 TeV

- No modification of charged jet production in p-Pb: $R_{pPb} \sim 1$
- Strong suppression of full jets in central Pb-Pb collisions

→ Suppression is due to final state effects in hot and dense QCD medium
Charged Jet $Q_{pPb}$

$Q_{pPb} \sim 1$ with no centrality dependence

⇒ High-$p_T$ hadron suppression in central Pb-Pb collisions is due to final state effects in hot and dense QCD medium
Jet structure in p-Pb

\[ R = \frac{dN_{pPb}}{dp_T (R = 0.2)} / \frac{dN_{pPb}}{dp_T (R = 0.4)} \]

No modification of jet structure compared to pp and model calculations
Baryon to meson production in jets different compared to inclusive production.

For comparison PYTHIA8 calculations (solid and dashed lines) are shown for p-Pb.

→ Baryon to meson enhancement from bulk of matter
Summary

• No modification of high-$p_T$ particle and jet production in p-Pb: $R_{p\text{Pb}} \sim 1$, $Q_{p\text{Pb}} \sim 1$

• No modification of jet structure ($R=0.2 / R=0.4$ yield ratio) in p-Pb compared to pp

• Indication of flow in high multiplicity p-Pb collisions

• Enhanced baryon to meson ratio from bulk of matter
Excellent particle Identification with ALICE


ITC

TOF

TRD

HMPID

TPC

22/7/15

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Reconstruction of decayed particles

Decay topology $\Xi^-$

$K^0_S \rightarrow \pi^+ \pi^-$

$\Lambda \rightarrow p\pi^-$

$\Xi^- \rightarrow \Lambda\pi^-$

ALICE, PRL 111 (2013) 222301

ALICE, PLB 728 (2014) 216
p-Pb Collisions at LHC

- Asymmetric p-Pb collisions at $\sqrt{s_{NN}}=5.02$ TeV: $p$ (4 TeV) + Pb (1.58 TeV/u)
  - Rapidity shift $\Delta y_{NN} = 0.465$ in the p-beam direction
- 2 beam configurations (p-Pb and Pb-p)

large $x$ from nucleus
“backward” antishadowing

small $x$ from nucleus
“forward” shadowing
Parton density from the NLO QCD fit to ZEUS e-p DIS data

Chekanov et al.

LHC: $x \sim 10^{-1}-10^{-5}$
Possibility to reach gluon saturation at small $x$ (Color Glass Condensate)

Iancu & Venugopalan, World Scientific 2003, 249
Nuclear Parton Distribution Functions – EPS09

Parton distribution function: medium vs. vacuum

\[ R_i^{Pb}(x, Q^2) \equiv f_i^{Pb}(x_1, Q^2) / f_i^p(x, Q^2) \]

NLO QCD fits to measured data (e-p, e-A, d-A)
Salgado et al. JHEP 0904:065, 2009

Valence quarks \( R_V^{Pb} \)  
See quarks \( R_S^{Pb} \)  
Gluons \( R_G^{Pb} \)

LHC: \( x \sim 10^{-1}-10^{-5} \) → Might influence the particle production.

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Double ridge in high multiplicity p-Pb collisions (similar to Pb-Pb)

\( v_2 \) for identified hadrons shows similar pattern to Pb-Pb

\( \rightarrow \) Indication of flow or other collective phenomenon?
$R_{p\text{Pb}}$ vs. models

ALICE, EPJ C 74 (2014) 3054

$R_{p\text{Pb}}$ vs. $p_T$ (GeV/c)

$\sqrt{s_{\text{NN}}} = 5.02$ TeV, charged particles, $|\eta_{\text{cms}}| < 0.3$

- ALICE (NSD)
- NLO pQCD: shadowing, EPS09s ($\pi^0$)
- LO pQCD + cold nuclear matter
- HIJING 2.1

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