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Identified charged hadron production at intermediate and high $p_T$ measured by the ALICE detector at the LHC

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Outline

- ALICE goal

- Charged hadrons identification at intermediate ($\approx$2 GeV/c - 10 GeV/c) and high $p_T$ ($\geq$ 10 GeV/c) with ALICE

- pp results

- p-Pb results

- Pb-Pb results

- nuclear modification factor in Pb-Pb and p-Pb collisions

- Conclusions
ALICE is designed to study the physics of strongly interacting matter under extremely high temperature and energy densities to investigate the properties of the quark-gluon plasma.

**Goals of the ALICE experiment**

- **proton-proton collisions:**
  - **high energy QCD reference.**
  - collected pp data at $\sqrt{s} = 0.9, 2.76, 5.02, 7, 8, 13$ TeV (2009-2012, 2015, 2016)

- **proton-nucleus collisions:**
  - **initial state/cold nuclear matter.**
  - collected p-Pb data at $\sqrt{s_{NN}} = 5.02, 8.16$ TeV (2012, 2013, 2016)

- **nucleus-nucleus collisions:**
  - **quark-gluon plasma formation!**
  - collected Pb-Pb data at $\sqrt{s_{NN}} = 2.76, 5.02$ TeV, (2010, 2011, 2015)
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ALICE has measured the yields of produced charged pions, kaons and protons, in a wide momentum range and in several colliding systems.
ALICE detectors: $\pi^\pm$, $K^\pm$ and $p(p\bar{p})$ PID

1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCal
8. DCal
9. PHOS, CPV
10. L3 Magnet
11. Absorber
12. Muon Tracker
13. Muon Wall
14. Muon Trigger
15. Dipole Magnet
16. PMD
17. AD
18. ZDC
19. ACORDE

a. ITS SPD (Pixel)
b. ITS SDD (Drift)
c. ITS SSD (Strip)
d. V0 and T0
e. FMD
ALICE exploits the combination of different particle identification (PID) techniques

- Energy loss (ITS, TPC)
- Time of flight (TOF)
- Cherenkov radiation (HMPID)
- Transition radiation (TRD)
- Calorimetry (EMCal/DCal, PHOS)
- Topological PID
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Intermediate, high $p_T$
ALICE detectors: $\pi^\pm$, $K^\pm$ and $p(\bar{p})$ PID

- PID performed by means of statistical unfolding on the time of flight.
- Time of flight measurements enable $3\sigma$ separation for $\pi/k$ up to 2.5 GeV/c and for $K/p$ up to 4 GeV/c.

- Up to 159 pad rows in Ne-CO$_2$ (Ar-CO$_2$) gas mixture: $\sigma_{dE/dx} \approx 5\%$.
- The largest separation is achieved at low-$p_T$ ($p_T \leq 0.7$ GeV/c).
- for higher $p_T$ (3-20 GeV/c) statistical PID is done exploiting the features of $dE/dx$ in the relativistic rise regime.

- PID performed by means of statistical unfolding on the Cherenkov angle.
- Cherenkov emission angle measurements enable $3\sigma$ separation for $\pi/k$ up to 3 GeV/c and for $K/p$ up to 5 GeV/c.
The inclusive charged pion, kaon and (anti)proton spectra are compared with pQCD NLO calculations using 3 different sets of identified FF functions (no protons FF for KRE).

The Kretzer Fragmentation Functions (KRE) describe well the charged particle spectra (Nucl. Phys. B 883 (2014) 615) and also the pions and the kaons.

Kaon spectra are well described by both DSS and KKP. Protons have largest differences.

The pQCD understanding of particle spectra is also important to determine the relative weight of quark and gluon jets in energy loss calculations.


KKP: Kniehl, Kramer, and Potter, NPB 582 (2000) 514

KRE: Kretzer, PRD 62 (2000) 054001

\( p_T \) spectra in pp collisions: comparison to NLO pQCD calculations

**ALICE**
$p_T$ spectra vs multiplicity in pp collisions

<table>
<thead>
<tr>
<th>Class name</th>
<th>I</th>
<th>II</th>
<th>III</th>
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<th>VI</th>
<th>VII</th>
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</tr>
</thead>
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<tr>
<td>$\sigma/\sigma_{\text{inel} &gt; 0}$</td>
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<td>4.7–9.5%</td>
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High mult.

Low mult.

pp @ 7 TeV
$p_T$ spectra vs multiplicity in pp collisions

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- High mult.
- Indication for collective effects, reminiscent of observed effects in Pb-Pb collisions attributed to radial flow

- Hardening with multiplicity and particle mass at low $p_T$ (< 2 GeV/c)

pp @ 7 TeV
Particle ratios in pp collisions

- $K/\pi$ shows no significant evolution with $\sqrt{s}$.

- The maximum value of the $p/\pi$ ratio shifts to slightly larger values of $p_T$ with increase of $\sqrt{s}$, consistent with hardening of the spectra with multiplicity across different energies.

- PYTHIA8 reproduces qualitatively the shape of the distribution but overestimates $p/\pi$ and underestimates $K/\pi$ at high $p_T$. 
Comparison of $p_T$-integrated yield ratios, measured at different $\sqrt{s}$:

- $p/\pi$ saturates at LHC energies
- $K/\pi$: no conclusion possible due to systematics
$\rho_T$ spectra in p-Pb collisions

- Hardening with multiplicity and particle mass.
- Reminiscent of observed effects in Pb-Pb:
  - Attributed to radial flow/recombination.
  - In hydrodynamic picture particles are pushed by the expanding hot medium.
  - Sensitive to pressure gradient and particle mass, indication for collectivity in p-Pb?

Results for low $\rho_T$: ALICE, PLB 728 (2014) 25-38
Particle ratios in p-Pb collisions

• p/π ratio:
  • shows a peak, which is more pronounced for higher multiplicities
  • drops to 0.1 at high $p_T$ (as in Pb-Pb).

• K/π ratio:
  • saturates at 0.5 for high $p_T$ (as in Pb-Pb).
  • does not show strong multiplicity dependence
For $p_T < 3$ GeV/$c$ a hardening of the spectra is observed going from peripheral to central events. This effect is mass dependent and is characteristic of hydrodynamic flow.

For high $p_T$ ($> 10$ GeV/$c$) the spectra follow a power law shape as expected from perturbative QCD.
Particle ratios in Pb-Pb collisions

- The $p/\pi$ peak at LHC is approximately 20% larger than at RHIC, consistent with an on-average larger radial flow velocity.
- The $K/\pi$ ratio measured by PHENIX is similar to the ALICE one.

$\sqrt{s_{NN}} = 2.76$ TeV

$\sqrt{s_{NN}} = 0.2$ TeV

ALICE 0-10% Pb-Pb

PHENIX 0-10% Au-Au

Particle ratios in Pb-Pb collisions

- Flat behavior of the $K/\pi$ ratio above $p_T > 2$ GeV/c.
- No evident energy dependence.
- No centrality dependence.
Proton spectra are harder than pions due to larger mass (same radial flow)

Larger radial flow at $\sqrt{s_{_{NN}}}$ = 5.02 TeV with respect to 2.76 TeV resulting in a shift of the $p/\pi$ maximum towards (slightly) higher $p_T$
**Particle ratios in Pb-Pb collisions: model comparison**


**TRENTo and AMPT initial conditions.**

Viscous hydrodynamics to describe the expansion of the QGP fireball.

Hadron cascade model (UrQMD) to simulate the evolution of the hadron resonance gas. Parameters are fine-tuned on data measured at 5.02 TeV.

- **K/π ratio:** Qualitative agreement with the measured data. Agreement gets worse from central to peripheral collisions.

- **p/π ratio:** Qualitative agreement with the measured data below 2 GeV/c. Agreement gets worse from central to peripheral collisions.
Particle ratios in Pb-Pb collisions: model comparison

McGill
Hydrodynamics + hadronic cascade hybrid approach. Initial conditions are generated via a new formulation of the IP-Glasma model and then evolved using relativistic viscous hydrodynamics, and finally fed into transport cascade in the hadronic phase.

worse agreement with respect to iEBE-VISHNU + AMPT/TRENTo. No significant centrality evolution of the ratio (no predictions for 60-80% centrality bins).
Particle ratios in Pb-Pb collisions: model comparison


Non uniform fireball divided in the core (high density) and corona (lower density).

- **K/π** ratio: good agreement especially at low and high $p_T$. Intermediate $p_T$ slightly off for central collisions.

- **p/π** ratio: bad agreement at intermediate and high $p_T$ in peripheral collisions.
How similar are the high $p_T$ ratios vs collision centrality?

- We have computed the integrated particle ratios for $10 < p_T < 20$ GeV/c.
  - charged particle tracking systematic uncertainty cancels.
  - $K/\pi$ ($p/\pi$) ratio as a function of $N_{\text{part}}$ is constant within the systematic uncertainty of $\approx 10\%$ ($\approx 20\%$) and it is consistent with the pp value (parton fragmentation in the vacuum).
For $2 < p_T < 8 – 10$ GeV/c: $R_{AA}$ for $\pi$ and $K$ are compatible and are smaller than $R_{AA}$ of $p$.

For $p_T > 8-10$ GeV/c: $R_{AA}$ for $\pi$, $K$ and $p$ are compatible.
• ALICE results are below the PHENIX values.
• Centrality evolution very similar.
• The pp spectra at LHC energies are significantly harder, so a larger energy loss is needed to get a similar $R_{AA}$. 
Comparison between 2.76 and 5.02 TeV data shows that the $R_{AA}$ does not depend on energy within uncertainties (other particle species can be found in the backup)
Nuclear modification factor: $R_{pPb}$

\[ R_{pPb} = \frac{d^2 N_{pPb}/dydp_T}{\langle T_{pPb} \rangle d^2 \sigma_{pp}^{INEL}/dydp_T} \]

\[ \langle T_{pPb} \rangle \sigma_{pp} = \langle N_{coll} \rangle \]

- $pp$ reference at $\sqrt{s_{NN}} = 5.02$ TeV is obtained interpolating available data (2.76 TeV and 7 TeV).
  - Power-law fit: $(\sqrt{s_{NN}})^\alpha$
  - Spectra in $pp$ at $\sqrt{s_{NN}} = 5.02$ TeV have been measured, $R_{pPb}$ will be soon updated. The measured spectra are compatible with the interpolated ones.
- Mass ordering in the Cronin peak, enhancement of protons.
- No suppression at high $p_T$ (> 8-10 GeV/c).
Conclusions

• The production of pion, kaon and proton at intermediate and high $p_T$ measured by ALICE in pp, p-Pb and Pb-Pb collisions has been presented.

• The inclusive charged pion, kaon, (anti)proton spectra in $\sqrt{s} = 2.76$ TeV pp collisions have been compared with pQCD NLO calculations. The Kretzer Fragmentation describes well pion and kaon spectra.

• Interesting similarities among different systems are observed: hints for the presence of collectivity in small systems.

• Particle ratios in Pb-Pb collisions have been compared to different hydrodynamic models
  • Qualitative agreement at low $p_T$ in central collisions. Agreement worsens in peripheral collisions. Hydro predictions have some difficulties at higher $p_T$.

• Nuclear modification factor in Pb-Pb collisions for high $p_T$ ($> \approx 10$ GeV/c) does not depend on particle species:
  • chemical composition of leading particles from jets traversing the medium is similar to that of vacuum jets.

• Nuclear modification factor in p-Pb collisions:
  • mass ordering in the Cronin peak, enhancement of protons.
  • No suppression at high $p_T$ → suppression observed in central Pb-Pb collisions is not due to an initial-state effect but to the hot matter created in heavy ion collisions.
Backup
• The PID responses for π, K, and p are Gaussians and independent of centrality.

• The background is caused by wrongly assigned rings, well reproduced by MC. It is described by a 6th degree polynomial. The small shoulder at $\theta_{\text{ch}} \approx 0.7$ rad which is an effect of the chamber geometry.
The PID responses for $\pi$, $K$, and $p$ are Gaussians ($e$ is < 1%). The means and widths are fixed to the calibrated values.
Measurements are combined using a weighted average where the weights are the systematic uncertainties (except for a common 3% uncertainty that is subtracted and directly added to the final spectrum).

ALICE Lower $p_T$ results (ITS+TPC +TOF) are from PRC 88 (2013) 044910.
The dE/dx response is calibrated using tracks identified from their time-of-flight (TOF) or topology (V⁰s and Γ–conversions).
The relative particle composition as a function of $p_T$

The fraction of $\pi$, $K$, and $p$ are extracted for each $|\eta|$ slice and then averaged for $|\eta|<0.8$. The final spectra are essentially obtained by multiplying with the invariant charge particle yields.
Spectra in pp collisions at 5 TeV
Invariant cross section for $\pi^0$ production at mid-rapidity in pp collisions at $\sqrt{s} = 200$ GeV
The behavior at high $p_T$ ($p_T > 10$ GeV/c) is independent of centrality (and the same as in pp collisions)
“Considering transverse fluid velocities up to $0.7c$, and thermal parton momentum distributions, one may get a “push” of a couple of GeV to be added to the transverse momentum of the string segment. This will be a crucial effect for intermediate $p_T$ jet hadrons.”
Intermediate $p_\text{T}$: comparison with EPOS

EPOS model 2.17-3

Hydrodynamical phase + hadronization processes at intermediate $p_\text{T}$ where the interaction between bulk matter and jets is considered

arXiv:1506.07287v1

Baryon-meson effect where a quenched jet hadronizes with flowing medium quarks

- centrality dependence well reproduced, even for very peripheral events.

- magnitude of both the $p$-to-$\pi$ and the $K$-to-$\pi$ peak is overpredicted.
The nuclear modification factor: $R_{AA}$

$$R_{AA} = \frac{d^2 N_{AA} / dp_T d\eta}{\langle T_{AA} \rangle d^2 \sigma_{pp} / dp_T d\eta}$$

$<T_{AA}>\sigma_{pp}=<N_{coll}>$

For $p_T < \approx 8 - 10$ GeV/$c$: $R_{AA}$ for $\pi$ and $K$ are compatible and are smaller than $R_{AA}$ for $p$.

At high $p_T$: $R_{AA}$ for $\pi$, $K$ and $p$ are compatible.
Hydrodynamic models describe well the spectra in central Pb-Pb collisions
The same models typically fail to describe the $p_T$ spectra in peripheral collision
Kraków+HKM: hydrodynamic (low $p_T$) models
Fries: recombination
3 quarks $\rightarrow$ baryon,
2 quarks $\rightarrow$ meson
EPOS: hydrodynamics (low $p_T$) $\rightarrow$ medium modified fragmentation for quenched jets (intermediate $p_T$) $\rightarrow$ vacuum fragmentation (high $p_T$)
Comparisons between the different colliding systems: high $p_T$ particle ratios in p-Pb and Pb-Pb
When the $p/\pi$ ratio in the peak is corrected for bulk effects using an $\eta$ gap one finds that the ratio is dominated by the bulk. So the ratio does not seem to be driven by hard physics.
Why do we expect particle species dependent modifications even at higher $p_T$?

- Large effects at intermediate $p_T$ – does this effect just disappear?
- The low value of $R_{AA}$ suggests that most hard partons interacts strongly with the medium

- Indirect
  - “in all models of radiative parton energy loss, the interaction of a parent parton with the QCD medium transfers color between partonic projectile and target. This changes the color flow in the parton shower and is thus likely to affect hadronization.”
- Direct
  - “In addition, flavour or baryon number could be exchanged between medium and projectile.”
A general model with particle species dependent modifications


(a) Fragmentation in vacuum

(b) Medium-modified fragmentation

- Effect inside jet
- But for $p_T > 8$ GeV/c we expect all hadrons to belong to jets
- Prediction incompatible with data
- Question: what do we learn about the interaction between parton and medium from this and similar models that are ruled out