Transverse momentum distribution of charged particles and identified hadrons in p–Pb collisions at the LHC

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p-Pb collisions

crucial to discriminate between initial (cold nuclear matter) and final state (QGP) effects
Identified-hadron analysis

ALICE sub-detectors relevant for identified-hadron analysis:

- **VZERO**: trigger, beam-BKG rejection, multiplicity classes
- **ITS**: tracking + vertexing
- **TPC**: tracking + vertexing + PID ($dE/dx$)
- **TOF (+T0)**: PID (time-of-flight)

\[ y_{\text{cms}} = 0.465 \]

\[ p-Pb \] multiplicity

- 0-5\% (high)
- ... (medium)
- 60-80\% (low)

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**Analysis and event-multiplicity selection**

**p-Pb collision data at** $\sqrt{s_{NN}} = 5.02$ TeV

asymmetric energy/nucleon in the beams

cms moves with $y_{\text{lab}} = 0.468$ (proton direction)

measurement performed in $0.0 < y_{\text{cms}} < 0.5$

The correlation between geometry and particle multiplicity is not straightforward as in Pb-Pb

We define seven p-Pb multiplicity event classes based on the amplitude of the signal of VZERO-A (V0A) detector

(A is the direction of Pb beam)

V0A signal proportional to charged-particle multiplicity in $2.8 < \eta_{\text{lab}} < 5.1$

from high- to low-multiplicity: 0-5% 5-10% 10-20% 20-40% ...
Transverse momentum spectra

$p_T$ spectra in several multiplicity classes

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Transverse momentum spectra

$p_T$ spectra in several multiplicity classes

$\pi^\pm$ \hspace{1cm} 0.2 – 3.0 GeV/c
$K^\pm$ \hspace{1cm} 0.25 – 2.5 GeV/c
$p(p)$ \hspace{1cm} 0.45 – 4.0 GeV/c
$K^0_S$ \hspace{1cm} 0 – 6.0 GeV/c
$\Lambda(\bar{\Lambda})$ \hspace{1cm} 0.6 – 6.0 GeV/c

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shows similar behaviour as observed in Pb-Pb collisions: significant increase at intermediate $p_T$ with increasing multiplicity corresponding significant depletion in the low-$p_T$ region. This is reminiscent of nucleus-nucleus phenomenology.
\( \Lambda/K_S^0 \) production ratio vs. \( p_T \)

- Systematic errors are largely correlated across multiplicity.

- Clear evolution with multiplicity in p-Pb.
  - Significant increase at intermediate \( p_T \) with increasing V0A multiplicity.

- Also this is reminiscent of nucleus-nucleus phenomenology...
  - Commonly understood in terms of collective flow and/or recombination.
➢ study and compare evolution of $p/\pi$ ratio in p-Pb and Pb-Pb in a quantitative way

- absolute $p/\pi$ values (at given $p_T$) differ for similar $dN_{ch}/d\eta$
- but similar increase of $p/\pi$ (at given $p_T$) for similar increase of $dN_{ch}/d\eta$

➢ enhancement and depletion seem to follow same $dN_{ch}/d\eta$ dependence

fit $p/\pi$ (at given $p_T$) vs. $dN_{ch}/d\eta$ with power-law ($y = A x^B$) both in p-Pb and Pb-Pb
**p/π production ratio: \( N_{ch} \) scaling**

Systematic errors are largely correlated across multiplicity/centrality.

- Enhancement and depletion seem to follow the same \( dN_{ch}/d\eta \) dependence.
- Fit \( p/\pi \) (at given \( p_T \)) vs. \( dN_{ch}/d\eta \) with power-law \( (y = Ax^B) \) behaviour.
- Same power-law scaling exponent \( (B) \) in p-Pb and Pb-Pb.

**Multiplicity dependence of \( p/\pi \) (at given \( p_T \)) independent of the colliding system**
similar study done also on the $dN_{ch}/d\eta$ dependence of $\Lambda/K^0_S$ ratio

...with very similar observations as in the $p/\pi$ case

multiplicity dependence of $\Lambda/K^0_S$ (at given $p_T$) independent of the colliding system

interestingly also valid in proton-proton collisions studied vs. multiplicity
Comparison to models

Blast-Wave fit:
Schnedermann, PRC 48, 2462 (1993)
➢ spectral-shape analysis performed with hydro-inspired model
➢ allows to characterize ID-spectra with small set of parameters

EPOS LHC:
Pierog, arXiv:1306.0121 [hep-ph]
➢ hard/soft scattering contribute to jet/bulk
➢ bulk matter described with hydro

Krakow:
Bozek, PRC 85, 014911 (2012)
➢ initial conditions form Glauber MC
➢ viscous hydrodynamic expansion
➢ statistical hadronization at freeze-out

DPMJET:
➢ QCD-inspired model
➢ reproduces $dN_{\text{ch}}/d\eta$ in NSD p-Pb

➢ **DPMJET fails** in describing distribution of ID-hadrons
➢ **Blast-wave, EPOS LHC and Krakow** give a reasonable description
Blast-Wave fit parameters

- p-Pb presents similar features as observed in Pb-Pb
- Parameters evolve with increasing multiplicity: larger $\langle \beta_T \rangle$, smaller $T_{fo}$
- Same results when including also $\Lambda$ and $K^0_s$ in the p-Pb global fit

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Blast-Wave fit parameters

➢ also PYTHIA shows similar features from this analysis
there is no hydro-like collectivity implemented in PYTHIA...
...but color reconnection (CR) produces flow-like patterns in pp

... and also proton-proton collisions show similar features

Blast-Wave analysis not yet conclusive
data do not exclude hydro/flow-like collective behavior in p-Pb

complementary information needed (ID-correlation analysis)

ALICE has measured the transverse momentum distribution of identified hadrons in p-Pb in several multiplicity classes

- $\pi^{\pm}$, $K^{\pm}$, $K_{S}^{0}$, $p(\bar{p})$, $\Lambda(\bar{\Lambda})$ spectra over a wide $p_{T}$ range
- clear $dN_{ch}/d\eta$ evolution of spectra (dynamical bias? radial flow?)

**Hadron-production vs. multiplicity**

- significant evolution of $p/\pi$ and $\Lambda/K_{S}^{0}$ vs. $p_{T}$ with $dN_{ch}/d\eta$
- $dN_{ch}/d\eta$ dependence independent of the colliding system

**Comparison to models and spectral-shape analysis**

- data better described by models including hydro (DPMJET fails)
- Blast-Wave fit of the data (characterize shapes with few parameters)
- similarities with Pb-Pb and pp (also in PYTHIA, no hydro there but flow-like)

**Analysis not yet conclusive on possible collective features in high-multiplicity proton-nucleus events**

- though current results are consistent with collective flow in p-Pb
Outline

ALICE overview and first p-Pb results
- charged-hadron production and $R_{AA}$
- central-barrel particle identification
- definition multiplicity classes

Transverse momentum spectra of identified hadrons
- $\pi^\pm$, $K^\pm$, $K^0_S$, $p(\bar{p})$, $\Lambda(\bar{\Lambda})$ over a wide $p_T$ range
  
  Identified-hadron production vs. multiplicity
- integrated production ratios and $\langle p_T \rangle$
- $p/\pi$ and $\Lambda/K^0_S$ vs. $p_T$ evolution
- comparison with Pb-Pb and pp results

Spectral-shape analysis and hydro models
- global Blast-Wave fits and parameters
- comparison with Pb-Pb, PYHTIA and pp

Summary and conclusions
The ALICE experiment at LHC

designed to cope with very high charged-particle multiplicities
\[ dN_{\text{ch}} / d\eta \leq 8000 \]

3D tracking with TPC
moderate B = 0.5 T
thin materials
for low-\(p_T\) particles

uses all known PID techniques
- \(dE/dx\)
- time-of-flight
- transition radiation
- Cherenkov radiation
- calorimetry
- muon filters
- topological decay

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**$p_T$** spectra and $R_{AA}$ in p-Pb collisions

- $p_T$ distribution of charged particles in NSD p-Pb collisions compared to pp reference

\[ R_{AA}(p_T) = \frac{\langle 1/N_{\text{evt}} \rangle d^2 N_{\text{ch}}^{AA} / d\eta dp_T}{\langle N_{\text{coll}} \rangle \langle 1/N_{\text{evt}}^{pp} \rangle d^2 N_{\text{ch}}^{pp} / d\eta dp_T} \]

Nuclear modification factor $R_{AA}$

- unity for hard-processes in the absence of nuclear modifications confirmed in Pb-Pb collisions at the LHC (direct-$\gamma$, $Z^0$ and $W^\pm$ production)

- $R_{AA}$ consistent with unity for $p_T > 2$ GeV/$c$
- the strong suppression observed in Pb-Pb is NOT an initial-state effect
- hot QCD matter effect

ALICE, PLB 696, 30 (2011)
ALICE, PRL 110, 082302 (2013)

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Particle-identification: $\pi^\pm K^\pm p(\bar{p})$

**TPC:** main tracking detector
PID via $dE/dx$ in gas
up to 159 samples, $\sigma \sim 5\%$

**TOF:** PID at intermediate momenta
PID via time-of-flight technique
$\sigma < 100$ ps
3$\sigma$ $K/\pi$ separation up to 2.5 GeV/$c$
3$\sigma$ $p/\pi$ separation up to 4.0 GeV/$c$
Topological reconstruction: $K^0_S \Lambda(\bar{\Lambda})$

**V0-decays: topological reconstruction identification over a large $p_T$ range**
- reconstruction of candidate weak-decays
- TPC $dE/dx$ selection of daughters
- invariant mass extraction of signal

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

$\Lambda \rightarrow p \pi^-$

$\bar{\Lambda} \rightarrow \bar{p} \pi^+$
Transverse momentum spectra

\[ \pi^\pm 0.2 \text{ – } 3.0 \text{ GeV}/c \]
\[ K^\pm 0.25 \text{ – } 2.5 \text{ GeV}/c \]
\[ p(p) 0.45 \text{ – } 4.0 \text{ GeV}/c \]
\[ K_S^0 0 \text{ – } 6.0 \text{ GeV}/c \]
\[ \Lambda(\bar{\Lambda}) 0.6 \text{ – } 6.0 \text{ GeV}/c \]

dotted lines: individual Blast-Wave fits for low/high-\(p_T\) extrapolation

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Particle ratios vs. charged-multiplicity

Systematic errors are largely correlated across multiplicity.

**K/π integrated ratio vs. dN_{ch}/dη:**
- in line with the trend of Pb-Pb and lower-energy RHIC results
- hints at a small increase with multiplicity also in p-Pb collisions

**p/π integrated ratio vs. dN_{ch}/dη:**
- in line with the values of pp, Pb-Pb and lower-energy RHIC results
- no significant evolution with multiplicity in p-Pb collisions

STAR, PRC 79, 034909 (2009)
PHENIX, PRC 69, 03409 (2004)
BRAHMS, PRC 72, 014908 (2005)
Particle ratios vs. charged-multiplicity

systematic errors are largely correlated across multiplicity

\[ \frac{\Lambda}{K^0_S} \text{ integrated ratio vs. } \frac{dN}{d\eta} : \]

- in line with the values of pp, Pb-Pb and lower-energy RHIC results
- no significant evolution from low to high multiplicity

\[ \frac{\Lambda}{\pi} \text{ integrated ratio vs. } \frac{dN}{d\eta} : \]

- in line with the values of pp, Pb-Pb and lower-energy RHIC results
- hints at a small increase at low multiplicity in p-Pb

STAR, PRC 79, 034909 (2009)
STAR, PRL 108, 072301 (2012)

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$\langle p_T \rangle$ vs. charged-multiplicity

Systematic errors are largely correlated across multiplicity

$\langle p_T \rangle$ increases with multiplicity in p-Pb for all particles

Mass ordering: larger mass $\Rightarrow$ larger $\langle p_T \rangle$
〈$p_T$〉 vs. charged-multiplicity

Systematic errors are largely correlated across multiplicity.

- P-Pb results show similar behavior as in Pb-Pb. 
  \[\langle p_T \rangle \text{ increases with multiplicity}\]
- P-Pb values higher than Pb-Pb for similar multiplicity.
  \[\text{Harder spectra}\]
- Pp minimum bias value in line with p-Pb trend.

STAR, PRC 79, 034909 (2009)
PHENIX, PRC 69, 03409 (2004)
BRAHMS, PRC 72, 014908 (2005)
$\langle p_T \rangle$ vs. charged-multiplicity

Systematic errors are largely correlated across multiplicity.

- p-Pb results show similar behavior as in Pb-Pb
  - $\langle p_T \rangle$ increases with multiplicity
- p-Pb values higher than Pb-Pb for similar multiplicity
  - Harder spectra
- pp minimum bias value in line with p-Pb trend
- Relative increase of protons (low/high multiplicity) softer than Pb-Pb
  - Different behavior wrt. pions and kaons
The $K/\pi$ production ratio vs. $p_T$ is shown in the figure. Systematic errors are largely correlated across multiplicity.

- Weak evolution with multiplicity in p-Pb.
- Small increase at intermediate $p_T$ with increasing V0A multiplicity, corresponding to small depletion in the low-$p_T$ region.
- Hints at similar behavior as observed in Pb-Pb collisions.
performed with hydro-motivated Blast-Wave model
Schnedermann, PRC 48, 2462 (1993)
aims at characterizing spectral shapes in multiplicity classes
with a small set of parameters

simultaneous fit of all spectra with 3 parameters
\( \langle \beta_T \rangle \) radial flow
\( T_{fo} \) freeze-out temperature
\( n \) velocity profile

global fit performed in the following \( p_T \) ranges:
\( \pi \) 0.5 – 1.0 GeV/c
\( K \) 0.3 – 1.5 GeV/c
\( p \) 0.5 – 2.0 GeV/c

Blast-Wave fits reasonable, though not very good
worse than central Pb-Pb
better than pp minimum bias

\[ \frac{1}{N_{ev}} \frac{d^2N}{dp_Tdp_y} \left[ \text{GeV/c}^2 \right] \]

\[ p_T \text{ (GeV/c)} \]

\[ \text{data / fit} \]

\[ p_{T} \text{ (GeV/c)} \]

V0A multiplicity
\[ p_{\text{Pb}} | s_{NN} = 5.02 \text{ TeV} \]

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p-Pb spectral-shape analysis

- performed with hydro-motivated Blast-Wave model
  Schnedermann, PRC 48, 2462 (1993)

- Blast-Wave fits reasonable, though not very good
  better than pp minimum bias:
  not successful at very low $p_T$

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p-Pb spectral-shape analysis

- performed with hydro-motivated Blast-Wave model
  Schnedermann, PRC 48, 2462 (1993)
- Blast-Wave fits reasonable, though not very good

worse than central Pb-Pb: successful up to higher $p_T$

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p-Pb spectral-shape analysis

- performed with hydro-motivated Blast-Wave model
  Schnedermann, PRC 48, 2462 (1993)
- adding $K_S^0$ and $\Lambda$
- global fit performed in the following $p_T$ ranges:
  - $\pi$: 0.5 – 1.0 GeV/c
  - $K$: 0.3 – 1.5 GeV/c
  - $p$: 0.5 – 2.0 GeV/c
  - $K_S^0$: 0.0 – 1.5 GeV/c
  - $\Lambda$: 0.6 – 2.0 GeV/c
- Blast-Wave fits reasonable, though not very good
  worse than central Pb-Pb
  better than pp minimum bias
p-Pb presents similar features as observed in Pb-Pb
parameters evolve with increasing multiplicity: larger $\langle \beta_T \rangle$, smaller $T_{fo}$
$T_{fo}$ is similar to Pb-Pb for similar multiplicity, $\langle \beta_T \rangle$ is larger in p-Pb
these observations seem to meet theoretical p-Pb predictions
stronger collective radial flow (smaller system) than Pb-Pb

p-Pb presents similar features as observed in Pb-Pb
parameters evolve with increasing multiplicity: larger $\langle \beta_T \rangle$, smaller $T_0$
$T_0$ is similar to Pb-Pb for similar multiplicity, $\langle \beta_T \rangle$ is larger in p-Pb
same results when including also $\Lambda$ and $K^0_S$ in the p-Pb global fit
Blast-Wave model – fit parameters

Schnedermann, PRC 48, 2462 (1993)

\[ \frac{dN}{p_\perp dp_\perp} \propto \int_0^R r \, dr \, m_\perp I_0 \left( \frac{p_\perp \sinh \rho}{T_{\text{kin}}} \right) K_1 \left( \frac{m_\perp \cosh \rho}{T_{\text{kin}}} \right) \]

\[ \rho = \tanh^{-1} \beta \]

\[ \beta = \beta_S (r/R)^n \]

\[ \langle \beta \rangle = \frac{2}{2+n} \beta_S \]

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Subtraction of secondary protons

ALI-PERF-47383

remove protons from weak decays
\[ \Lambda \rightarrow p \pi^- \]
\[ \Sigma^+ \rightarrow p \pi^0 \]

remove protons knocked out from the material

use measured DCA distribution and fit it with MC templates
TOF raw yield extraction

2.4 < p_T < 2.5 GeV/c minimum bias

3.8 < p_T < 4.0 GeV/c minimum bias

ALI-PERF-47391

ALI-PERF-47395

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