Identified particle production in p-Pb measured with the ALICE detector

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Outline

• Introduction
• Particle IDentification (PID) with ALICE
• Measurements of $p_T$ spectra of $\pi, K, K^0_S, \rho, \text{and } \Lambda$
• Theory motivated interpretations
• Data driven interpretation
• Discussion
• Conclusions
A simple pre-LHC physics picture of different colliding systems

<table>
<thead>
<tr>
<th></th>
<th>Inelastic pp</th>
<th>Pb-Pb</th>
<th>Inelastic p-Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial interactions</td>
<td>Color transfer between partons</td>
<td>Interactions between dense gluon fields</td>
<td>Dense gluon fields (Pb) probed by partons (p)</td>
</tr>
<tr>
<td></td>
<td>Multi Parton Int.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cold Nuclear Matter</td>
<td>No</td>
<td>Yes (e.g. J/Psi ”absorption”)</td>
<td>Yes</td>
</tr>
<tr>
<td>Hot Nuclear Matter</td>
<td>No</td>
<td>Hydrodynamic expansion, quenching, quarkonia dissociation, ....</td>
<td>No</td>
</tr>
<tr>
<td>Hadronization (Chemical freezeout)</td>
<td>String breaking MPI: color reconnection</td>
<td>Statistical model</td>
<td>Closer to pp</td>
</tr>
<tr>
<td>Kinetic freezeout</td>
<td>No</td>
<td>Hadronic rescattering</td>
<td>No</td>
</tr>
</tbody>
</table>

Pre-LHC questions for p-Pb physics:
Are the dense gluon fields well described by CGC?
What is the magnitude of cold nuclear matter effects?
Using Particle IDentification to study the double ridge

Pion-hadron correlations

Proton-hadron correlations

See talk by Paul Kujier

Using Particle IDentification to study the double ridge

• Clear mass ordering

Fourier coefficients:

See talk by Paul Kujier

New questions for p-Pb collisions

- What is the origin of the double ridge structure observed in p-Pb collisions?
  - Initial state effects? (CGC?)
  - Formation of collective medium? (hydrodynamics?)
    - Is this a Hot or “Cold” QCD effect?
    - Alternative explanation?
- Strong indications for a coming paradigm change!
- Question: what can we learn from bulk production of identified particles?
  - Are there indications for final state effects such as radial flow?
ALICE: trigger and multiplicity

\[ p \quad \longleftrightarrow \quad Pb \quad (y_{CM} = y_{LAB} + 0.465) \]

- VZERO used for triggering and multiplicity (A side)
- Fluctuations in the number of hard scatterings are important because of the small number of participants \( \Rightarrow \) weaker multiplicity vs. impact parameter correlation than in Pb-Pb

See talk by Alberica Toia
ALICE: tracking and PID

\[ p \rightarrow \rightarrow Pb \quad (\gamma_{CM} = \gamma_{LAB} + 0.465 \rightarrow) \]

- Detectors used in this analysis
  - Inner Tracking System (tracking, PID)
  - Time Projection Chamber (tracking, PID)
  - Time Of Flight (PID)
Identification of primary tracks

p-Pb event display
\( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)
Spectra of $\pi$, $K$, $p$ in $p$-Pb collisions

- Rapidity interval $0 < y_{CM} < 0.5$
- Dashed lines are individual blast-wave fits
Topological identification of $V^0_s$s

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

$\Lambda \rightarrow p + \pi^-$
Spectra of $K^0_S$ and $\Lambda$ in p-Pb collisions

- Rapidity interval $0 < y_{CM} < 0.5$
- Dashed lines are individual blast-wave fits

$\rho_T$ coverage:
- $\pi$: $0.2 < \rho_T < 3.0$ GeV/c
- $K$: $0.25 < \rho_T < 2.5$ GeV/c
- $K^0_S$: $0.0 < \rho_T < 8.0$ GeV/c
- $p$: $0.45 < \rho_T < 4.0$ GeV/c
- $\Lambda$: $0.6 < \rho_T < 8.0$ GeV/c
Features of the data

- Characteristic evolution of $p/\pi$ and $\Lambda/\bar{K}^0_S$ with multiplicity is reminiscent of Pb-Pb where it is believed to be due to radial flow
- NB! The solid boxes for p-Pb ratios indicate the uncorrelated systematic error
  $\Rightarrow$ the relative trend can be measured rather precisely

Integrated particle ratios and $<p_T>$ will be covered by Francesco Barile
Which models can capture these features?

- **Models**
  - Blast-wave (next slides)
  - EPOS LHC (full event generator including hydro)
  - Krakow (hydro calculation focused on low $p_T$)
  - DPMJet (PHOJET pp + nuclei via Glauber-Gribov theory)

- Only models which employ hydrodynamics can describe the $p_T$ spectra
A blast wave study of the data

p-Pb 0-5%

- Simultaneous fits
  \( \pi: 0.5 < p_T < 1.0 \text{ GeV/c} \)
  \( K: 0.2 < p_T < 1.5 \text{ GeV/c} \)
  \( pp: 0.3 < p_T < 1.5 \text{ GeV/c} \)
  \( p: 0.3 < p_T < 3.0 \text{ GeV/c} \)
  \( pp: 0.5 < p_T < 2.5 \text{ GeV/c} \)

- Adding
  \( K^0_S \) (0.0 < \( p_T \) < 1.5 GeV/c)
  and
  \( \Lambda \) (0.6 < \( p_T \) < 2.0 GeV/c)
  does not significantly change extracted parameters


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

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

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

\[
\langle \beta_T \rangle = \frac{2}{2+n} \beta_S
\]
A blast wave study of the data

The description of p-Pb and pp data by the blast-wave fit is reasonable without being excellent
A blast wave study of the data

The $p_T$ region where the blast-wave fit describes the data is in general broader for Pb-Pb
Summarizing the results from the blast-wave studies

There is a strong common trend between the parameters extracted from Pb-Pb and p-Pb
Summarizing the results from the blast-wave studies

Even the pp data seems to follow the same trend!
It seems that if we ascribe the change in spectral shape to radial flow in p-Pb then the same can be done in pp.
Summarizing the results from the blast-wave studies

BUT also simulated PYTHIA8 pp events follow a qualitatively similar trend when Color Reconnection (CR) is enabled. CR has been shown to mimic radial flow but without requiring the formation of a medium [Ortiz et al, PRL111, 042001 (2013)]

⇒ No unique theoretical interpretation of hydro/medium
⇒ Can we learn more in another way?
Data driven approach

- Fit the evolution of the $p/\pi$ ratio with $dN/d\eta$ in each $p_T$ interval with a power law function: $y = Ax^B$
Data driven approach

- Fit the evolution of the $p/\pi$ ratio with $dN/d\eta$ in each $p_T$ interval with a power law function: $y = Ax^B$
- Compare the extracted exponents $B$

arXiv:1307.6796
Similar studies with $\Lambda/K^0_S$

- Using $\Lambda/K^0_S$ allows one to extend the $p_T$ range to cover also the region of the baryon peak ($p_T \sim 3\text{GeV}/c$) where the scaling also seems to hold.
The way the multiplicity is defined in pp biases the $p/\pi$ ratios (significantly more than the $\Lambda/K^0_S$)

The evolution of $\Lambda/K^0_S (p/\pi)$ with $dN/d\eta$ is similar for all 3 (2) systems

⇒ surprising suggestive pattern that similar physics is driving the ratios for all systems and for all sizes (no evidence for an onset in $dN/d\eta$) ....
.... but it also raises additional questions

• Is the scaling in particle ratios and dN/d\( \eta \) meaningful?
  – They do not appear to be particularly fundamental quantities in e.g. a hydro model?

• What is the role of the initial geometry?
  – For pp and p-Pb it is limited by proton area suggesting a weak multiplicity dependence of the initial area
  While for Pb-Pb the nuclear overlap has a strong multiplicity dependence

• How does the absolute dN/d\( \eta \) affect this?
  – Varying e.g. the center of mass energy?

• Have a look at the last two questions here
Geometry: is the Pb-Pb centrality evolution described by hydro?

- Near ideal hydrodynamics with some implementation of the hadronic phase describes well $p_T$ spectra in central collisions
Geometry: is the Pb-Pb centrality evolution described by hydro?

- The same models fail to describe the $p_T$ spectra in peripheral collisions.
- Typically hydro has not been expected to work in peripheral collisions but if it is at work in p-Pb and pp collisions should it not work there?


$1/N_{ev} 1/(2\pi p_T) d^2 N/ dp_T dy$ (GeV/c)^2

$\pi^+ + \pi^-$

$K^+ + K^-$

$\bar{p} + p$
How does varying $\sqrt{s_{NN}}$ affect the ratios?

At RHIC $\Lambda$-bar / $\Lambda$ $\sim$ 0.8.

In the statistical model for fixed $T$ and $\mu_B << T$ one expects $(\Lambda+\Lambda$-bar)/$K^0_s$ to be insensitive to $\mu_B$.

So if the underlying ratios are similar we expect LHC ratios to lie between RHIC ratios.

- For peripheral events (blue points) the ratios are similar while for central events (red points) there is a clear difference.

- The absolute increase of $dN/d\eta$ from RHIC to LHC is $\sim$2.1 in both centrality classes.

$\Rightarrow$ Different scaling at RHIC and LHC.

$\Rightarrow$ The smaller peripheral system seems less responsive to the increase in energy density.

Is this consistent with hydrodynamics in small systems?
Conclusions

- The $p_T$ spectra of $\pi$, $K$, $K^0_s$, $p$, and $\Lambda$ as a function of multiplicity in p-Pb were reported.
- These p-Pb spectra show similar trends as associated with radial flow in Pb-Pb:
  - Spectra are best described by models incorporating a hydrodynamical phase
  - Blast-wave analysis shows similar multiplicity dependence as in Pb-Pb
  - The evolution of particle ratios with $p_T$ and multiplicity seems to follow the same trend across all collision systems
- Taken together there are strong indications for final state effects in both p-Pb (and pp), but some uncertainty as to whether this is hydrodynamical or due to another mechanism
Backup slides
7 TeV pp spectra vs mult
7 TeV pp ratios vs mult

Identified particles in p-Pb by ALICE (P. Christiansen, Lund)
The double ridge in p-Pb collisions

- Double ridge structure
- Reminiscent of azimuthal flow in Pb-Pb collisions
Sum of particles and antiparticles

- At lower CM energies $\Lambda$-bar/ $\Lambda << 1$.
- In the statistical model (neglecting feeddown):
  - $N_\Lambda \propto e^{+\mu B/T} * e^{-m/T}$
  - $N_{\Lambda\text{-bar}} \propto e^{-\mu B/T} * e^{-m/T}$
- When $\mu_B << T$:
  - $N_\Lambda + N_{\Lambda\text{-bar}} \propto (1 + \mu B/T + 1 - \mu B/T) * e^{-m/T} \sim 2*e^{-m/T}$
- So $(N_\Lambda + N_{\Lambda\text{-bar}})/(2*NK^0_s)$ is roughly independent of $\mu_B$. 