Identified charged pion, kaon, and proton production in pp and Pb-Pb collisions at LHC energies measured with ALICE
The nuclear modification factor $R_{AA}$ for unidentified hadrons

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

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

$N_{\text{coll}}$ is the number of binary collisions.

For perturbative QCD processes:

$R_{AA} < 1$: suppression

$R_{AA} = 1$: no nuclear effects

$R_{AA} > 1$: enhancement

Identified charged pion, kaons, and proton production in pp and Pb-Pb Collisions

EPSHEP 2013, P. Christiansen (Lund University)
What happens when we collide Pb-Pb: 3 answers?

**SOFT**

- Non-perturbative physics
- Bulk properties (=medium)
  - “Low $p_T$”

**PID**: ratios and flow

---

**HARD**

- Perturbative physics
- Rare process: jet (=probe)
  - “High $p_T$”

**PID**: jet quenching

---

**INTERMEDIATE**

- Interplay between soft and hard?
  - **PID**: baryon anomaly
The ALICE experiment is optimized for charged particle tracking and hadron identification for $|\eta|<0.8$.

Pb+Pb @ $\sqrt{s}$ = 2.76 ATeV
2011-11-12 06:51:12
Fill : 2290
Run : 167693
Event : 0x3d94315a
The ALICE experiment is optimized for charged particle tracking and hadron identification for $|\eta|<0.8$. The ALICE as a charged PID detector (central barrel)
Identified charged pion, kaons, and proton production in pp and Pb-Pb Collisions

EPSHEP 2013, P. Christiansen (Lund University)


Statistical model calculations agrees with most ratios. Proton disagreement might indicate: non-equilibrium effects [arXiv:1303.2098], annihilation in hadronic stage [arXiv:1212.2431], or a flavor hierarchy of freeze-out temperatures [PRD 85, 014004 (2012)].
Particle identification at high $p_T$ using TPC dE/dx

Pushing the separation to the relativistic rise

Identified charged pion, kaons, and proton production in pp and Pb-Pb Collisions

EPSHEP 2013, P. Christiansen (Lund University)
Particle identification at high $p_T$ using TPC $dE/dx$

Baryon anomaly in central Pb-Pb. Quark recombination?

Identified charged pion, kaons, and proton production in pp and Pb-Pb Collisions

18/7-2013
Particle identification at high $p_T$ using TPC $dE/dx$

**pp**

Baryon anomaly in central Pb-Pb. Quark recombination?

$\downarrow$

Baryon anomaly not observed at high $p_T$, opposite to what was speculated pre-LHC.

**central Pb-Pb**

Identified charged pion, kaons, and proton production in pp and Pb-Pb Collisions

EPSHEP 2013, P. Christiansen (Lund University)
Identified π, K, and p spectra

$\pi^+$, $\pi^-$

$K^+$, $K^-$

$p + \bar{p}$
Identified high $p_T$ production is not well described by theory. The peak in the proton to pion ratio in PYTHIA is related to color reconnection which gives a flow-like effect [arXiv:1303.6326]
For $p_T < 8$ GeV/c: $R_{AA}$ for $\pi$ and K compatible and smaller than $R_{AA}$ for p.
At high $p_T$ above 10 GeV/c the $R_{AA}$ for $\pi$, K and p are compatible. This suggest that leading particle jet hadron chemistry (flavor or baryon number transfer, and color flow) effects are small if present
The dominant effect is the collective medium response.

The dominant effect that can be observed with PID is at $p_T < 8 \text{ GeV/c}$ and due to the medium. Hydrodynamics, recombination, or?
Particle ratios compared to models

Krakow+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 $p_T$)

Krakow: PRC85, 064915 (2012)
HKM: PRC87, 024914 (2013)
Fries: PRL90, 202303 (2003) and private communication
EPOS: PRL109, 102301 (2012) and private communications
Comparing pions and protons to heavy mesons: $\phi$ (1020)

The $R_{AA}$ for $\phi$ mesons follows $p$ for $p_T < 2$ GeV/c (hydrodynamic medium region).
For $p_T > 2$ GeV/c the $R_{AA}$ for $\phi$ mesons is in between $\pi$ and $p$. 

Identified charged pion, kaons, and proton production in pp and Pb-Pb Collisions
EPSHEP 2013, P. Christiansen (Lund University)
Conclusions

- The low $p_T$ spectra can be described by hydrodynamics and most yields are in agreement with statistical model predictions.

- The $R_{AA}$ for pions, kaons, and protons for $p_T > 8-10$ GeV/c shows no particle species dependence suggesting that there is little interplay between the fragmentation process and the medium.

- The intermediate $p_T$ region ($2 < p_T < 8$ GeV/c) is rich in exciting physics where PID provides much additional information as can be seen in the large baryon to meson ratio.

Thank you!
Backup slides
Identified charged pion, kaons, and proton production in pp and Pb-Pb Collisions

When the p/π ratio in the peak is corrected for bulk effects using an η gap one finds that the ratio is dominated by the bulk.
So the ratio does not seem to be driven by hard physics.
The ALICE experiment at LHC

Identified charged pion, kaons, and proton production in pp and Pb-Pb Collisions
EPSHEP 2013, P. Christiansen (Lund University)
TPC dE/dx performance at low $p_T$
Several models capture the essential features (but some miss absolute scale).

The relative particle species dependent effects should be easier to describe as complicated space time dynamics probably falls out in the “double ratio”.

\[
R_{AA} = \frac{d^2N^{AA}/dp_Td\eta}{\langle T_{AA} \rangle d^2\sigma^{pp}/dp_Td\eta}
\]
EPOS: baryon to meson enhancement (1/2)

Hard scatterings only, but 3 possibilities for produced string segments

- no energy to escape $\rightarrow$ hydrodynamically “soft hadrons”
- energy to escape and formed outside bulk $\rightarrow$ jets
- energy to escape, but formed inside bulk $\rightarrow$ affected by the flowing matter (“fluid-jet interaction”).

EPOS2.17v3
K. Werner,
Calculation for $\Lambda/K^0_s$. 

18/7-2013
Identified charged pion, kaons, and proton production in pp and Pb-Pb Collisions 
EPSHEP 2013, P. Christiansen (Lund University)
“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.”
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, flavor or baryon number could be exchanged between medium and projectile.”
A general model with particle species dependent modifications


- Effect inside jet
- But for $p_T >> 8 \text{ GeV/c}$ we expect all hadrons to belong to jets
- Prediction incompatible with data
- Question: what do we learn about the interaction between parton and medium?

Identified charged pion, kaons, and proton production in pp and Pb-Pb Collisions
EPSHEP 2013, P. Christiansen (Lund University)
Color anomalous baryons fragmentation

- Color anomalous baryon fragmentation (P. Aurenche, B.G. Zakharov, Eur.Phys.J. C71 (2011) 1829.). The model is aimed at explaining the baryon anomaly but these effects persist out to higher $p_T$.
  - A hard scattered quark (triplet) can pickup a gluon from the medium $\rightarrow$ sextet state
  - a gluon (octet) can pick up another gluon $\rightarrow$ decuplet state
  - The fragmentation of these color states is very different from normal quark (triplet) and gluon (octet) states and relies on string junction (soft effect).

**Fig. 1** The $q \rightarrow gq$ (a) and $g \rightarrow gg$ (b) transitions in the medium and possible color states of the final two parton systems
Elliptic and triangular flow for identified particles at high $p_T$

- The $v_2$ and $v_3$ also peaks in the intermediate $p_T$ region
  - Large particle species dependence
- End of hydrodynamic flow for $p_T \geq 9-10$ GeV/c
  - Triangular flow which is not sensitive to collision geometry becomes small
  - No or small particle species dependence for $v_2$ (little mass dependence)
  - And pion $v_2$ is well described by jet quenching prediction