Soft Probes of the QGP measured by ALICE

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Heavy-Ion Collision

- $p_T$ spectra $\rightarrow T_{fo}$ and radial flow
- The relative abundance of hadrons $\rightarrow T_{ch}$
- Flow $\rightarrow$ initial conditions and dynamic properties (e.g. viscosity)
- Quantum correlations (e.g. HBT) $\Rightarrow$ Radii

$p$-A collisions $\Rightarrow$ info on initial conditions; at LHC more like pp or A-A?
ALICE Detector

Key sub-detectors for analysis of soft probes:

- Inner Tracking System (ITS)
- Time Projection Chamber (TPC)
- Time of Flight (TOF) + T0
- Trigger and centrality V0
Pb-Pb and p-Pb particle spectra in hydro picture

Central collisions are well described by hydro

p-Pb are better described by models with hydro
Blast-wave is an approximation of a hydrodynamic evolution

The same trend for p-Pb as for Pb-Pb \( \Rightarrow \) radial flow in p-Pb?
Hadron-chemistry $pp$, $p$-$Pb$, $Pb$-$Pb$

$pp \Rightarrow p$-$Pb \Rightarrow Pb$-$Pb$

$\rightarrow$ strangeness enhancement
Hadron-chemistry pp, p-Pb, Pb-Pb

\( \text{pp} \rightarrow \text{p-Pb} \rightarrow \text{Pb-Pb} \)

- strangeness enhancement
- deuteron enhancement

ALICE Preliminary

- Extrapolated (Pb-Pb 0-10%)
- Extrapolated (p-Pb 0-5%)

- pp \( \sqrt{s} = 7 \) TeV
- p-Pb \( \sqrt{s_{NN}} = 5.02 \) TeV
- V0A Multiplicity (Pb-Side) 0-5%
- Pb-Pb \( \sqrt{s_{NN}} = 2.76 \) TeV, 0-10%
Hadron-chemistry pp, p-Pb, Pb-Pb

\[ \text{pp} \Rightarrow \text{p-Pb} \Rightarrow \text{Pb-Pb} \]

- strangeness enhancement
- deuteron enhancement
- \( K^* \) suppression
Hadron-chemistry pp, p-Pb, Pb-Pb

pp => p-Pb => Pb-Pb

➔ strangeness enhancement
➔ deuteron enhancement
➔ K* suppression
➔ Baryon suppression (p/π and Λ/K0S ratios)
Statistical model vs. Pb-Pb data

- Pb-Pb data described by statistical models $T_{ch} \approx 156$ MeV and $\mu_B = 0$ MeV
- Puzzle $\Rightarrow$ proton yield overestimated by models
- Many explanations on the market:
  - non-equilibrium description
  - annihilation in hadron gas
  - mass ordering of the phase transition
  - missing mass states
Flow

Hydrodynamic evolution of the system transforms the space anisotropy of initial condition:

Flow coefficients into momentum space:

\[ v_n = \langle \cos(n(\phi - \Psi_n)) \rangle \]

\[ \frac{d^3 N}{dp^3} \propto 1 + \sum_{n=0}^{\infty} 2v_n \cos(n(\phi - \Psi_n)) \]
Flow of identified particles in Pb-Pb

→ Mass ordering $p_T < 3$ GeV/$c$ + crossing point position ($p_T = 2 - 3$ GeV/$c$) effects of the radial flow
→ For $p_T > 3$ GeV/$c$ particles seem to group into mesons and baryons
→ $v_2$ of $\phi$ follows baryons for central collisions and shift progressively to mesons for peripheral collisions
Number of constituent quark scaling in Pb-Pb

ALICE 10-20% Pb-Pb \( s_{NN} = 2.76 \) TeV

\[ V_2(\Delta \eta > 0.9)/n_q \]

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

ALICE 40-50% Pb-Pb \( s_{NN} = 2.76 \) TeV

\[ V_2(\Delta \eta > 0.9)/n_q \]

\[ p_T/n_q (\text{GeV/c}) \]
Number of constituent quark scaling in Pb-Pb

NCQ scaling, if any, is only approximate (±20%) for $p_T/n_q > 1$ GeV/c
Flow in Pb-Pb vs. hydrodynamics

- Hydrodynamical model + hadronic cascade (VISHNU) qualitatively agrees with data
- Wrong mass ordering for p and Λ or overestimation for φ, can be due to a not-perfect description of the hadronic cascade phase (x-sections)
p-Pb surprise

In p-Pb collisions $v_2$ for identified hadrons calculated using two-particle correlations

The same trend observed as for Pb-Pb
Comparison of $v_2$ for p-Pb and Pb-Pb

$\text{Higher particle cumulants suppress now-flow correlations}$

$\text{Correlations observed in p-Pb extend to more than 2-particle}$
The size of the source comes from identical boson correlations (low $p_T$ pions).

- Pb-Pb results show hydrodynamic evolution.

- Predictions and results for p-Pb inconclusive => both scenarios (with and without hydro) still open.
Conclusions

- ALICE has confirmed the creation and the collective expansion of the QGP during Pb-Pb collisions
- Results in a good agreement with the hydrodynamic picture
- Some observations in Pb-Pb collisions not fully understood (e.g. proton yields)
- p-Pb collisions showed some similarities with Pb-Pb collisions, hydro needed in p-Pb?
- Looking forward to run 2 and the new energy regime