Results on Thermalisation and Harmonics from ALICE

Anthony Timmins for the ALICE Collaboration
Overview

1. **ALICE performance**
   - Detector overview and capabilities
   - Delivered luminosities

2. **Identified particle production and thermalisation**
   - Chemical freeze out and radial flow in Pb-Pb
   - Strangeness dependent freeze out temperatures
   - Radial flow studies in p-Pb collisions

3. **Flow harmonics and initial conditions**
   - $v_n$ fluctuations
   - Chiral Magnetic Effect (CME) searches
   - Event shape engineering
   - Multi-particle correlations and mixed harmonics
The ALICE detector
Suite of detectors available, ALICE optimised for PID
Angular correlation capacities

- Highly uniform TPC $\phi$ distribution
  - Extended to TPC tracks with ITS hits
- VZERO detectors
  - Large $\eta$ separation from TPC
  - Minimises non-flow in reaction plane studies
LHC heavy-ion running

<table>
<thead>
<tr>
<th>Year</th>
<th>System</th>
<th>Energy $\sqrt{s_{\text{NN}}}$ (TeV)</th>
<th>Delivered Integrated luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>Pb-Pb</td>
<td>2.76</td>
<td>10 $\mu$b$^{-1}$</td>
</tr>
<tr>
<td>2011</td>
<td>Pb-Pb</td>
<td>2.76</td>
<td>0.1 nb$^{-1}$</td>
</tr>
<tr>
<td>2013</td>
<td>p-Pb</td>
<td>5.02</td>
<td>30 nb$^{-1}$</td>
</tr>
</tbody>
</table>

- **Two Pb-Pb runs**
  - In 2010 - commissioning and first data taking
  - In 2011 – Second run, factor 10 increase in luminosity

- **p-Pb occurred this year**
  - LHC delivered target luminosity

- **Long shutdown now (LS1)**
  - Various upgrades and maintenance in progress
Provide key information on freeze-out dynamics

- Spectral shapes vs. mass => **Radial flow** and **kinetic freeze-out** temperatures
- Yields and ratios => **Chemical freeze-out** temperatures
**Identified particle spectra**

- Central Pb-Pb $\pi, K, p$ spectra published last year
  - $K^0_S, \Lambda, \Xi$ and $\Omega$ spectra just submitted for publication
  - arXiv's 1307.6796, 1307.5543 and 1307.5530

- **Shallower slopes** compared to RHIC data...

- Blast-wave model used to obtain radial flow velocity:
  - $\langle \beta_T \rangle = 0.65c$
  - 10% higher than RHIC
  - $T_{\text{kinetic}} = 80$-$95$ MeV

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**Graphical representation**

- Various particle spectra and fits shown, including $\pi^+ + \pi^-$, $K^+ + K^-$, and $p + \bar{p}$, with fits indicating shallower slopes compared to RHIC data.

- Blast wave model parameters: $\langle \beta_T \rangle = 0.65c$, 10% higher than RHIC, $T_{\text{kinetic}} = 80$-$95$ MeV.
Chemical freeze-out fits

*Chemical freeze-out fits with just π, K, p data:*
- $T_{ch} \sim 170$ MeV
- Similar to RHIC data

*Deviations observed for proton data...*
Inclusion of strangeness yields

- **Difficult to fit all yields** well with common $T_{\text{chem}}$
  - Higher $T_{\text{chem}}$ suits multi-strange, lower $T_{\text{chem}}$ suits proton and $\Lambda$

- **$K^*0$ not included in fit…**

- **Particle dependent $T_{\text{chem}}$?** Differing particle re-scattering?

**Graph:**
- Data: ALICE, 0-10%
- Thermal model fit, $\chi^2/N_{\text{df}}=30.9/12$
- $T=156 \text{ MeV}, \nu=5380 \text{ fm}^3$ ($\mu_b = 1 \text{ MeV fixed}$)
- $T=164 \text{ MeV}, \mu_b = 1 \text{ MeV}, \nu=4499 \text{ fm}^3$ (norm. to $\pi^+$)

**ALICE PRELIMINARY**

**ALI-PREL-57339**
Radial flow studies in p-Pb in collisions

Resembles Pb-Pb: mean $p_T$ increases with centrality and mass

- Blast wave fits $<\beta_T> \sim 0.5c$ central p-Pb
- Similar values observed in pp

More details see talk by P. Christiansen on Thursday…
Flow harmonics and initial conditions

Many tools to investigate fluctuations in initial conditions with flow harmonics:

- Comparison of 2 and 4 particle flow cumulants
- Unfolded $v_2$ distributions
- Multi-particle correlations and mixed harmonics
Differences in $v_2\{2\}$ and $v_2\{4\}$ arise from $v_2$ fluctuations

- Strength of flow fluctuations $\sigma_{v_2}$ can also be determined

- $v_2\{4\} \sim v_2\{6\} \sim v_2\{8\}$ characteristic of Bessel Gaussian form for $v_2$ fluctuations
v_2 and v_3 fluctuations

- Large fluctuations in v_2^2 and v_3^2 observed event by event
  - Appear largely independent

- 2 particle correlations in circled events dominated by v_2 and v_3
  - Allows v_n distributions to be obtained...

\[
V_{n\Delta} = v_n^2
\]
Unfolded $v_2$ distributions

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

Method: $v_2^2 = V_2^2, p_T > 0.15$ GeV/c
- Bessel-Gaussian fit

Unfolding removes effects of finite statistics

- Expected to reflect eccentricity fluctuations of initial state (arxiv:1212.1008)
- Bessel Gaussian fits work nearly always.
Multi-particle correlations of $v_1$ and $v_3$

- Multi-particle correlations $v_n\{4\}$, $v_n\{6\}$, and $v_n\{8\}$ less sensitive to non-flow
- Strong signals observed for $n=1,2$ and 3
  - Suggests driven by collective effects
- $v_1\{4\} \sim v_1\{6\} \sim v_3\{4\} \sim v_3\{6\}$...

Submitted $v_1$ vs. reaction plane for publication
(arXiv:1306.4145)
Event shape engineering

- If we can “see” events with low/high flow, we can select them.
  - Need to be clever and avoid biases.

- Measure flow in one part of phase space (a)
  - Analyze data in another part (b)

- Appears to work in data
  - Select events with low/high $q_n^2$ in VZERO
  - Observe low/high $v_2$ measurements in TPC…

\[ q_n^2 = 1 + (M - 1)v_n^2 \]
Event shape engineering

- Spectra shape appears to change with $q_2$
  - $<p_T>$ increases with $v_2$
  - No obvious mass dependence

- Due to correlation between $<\epsilon_2>$ and $<R^2>$?
  - High $<\epsilon_2>$, small $<R^2>$, greater radial pressure gradient?

- Other observables we can study w.r.t $q_2$?
Searches for Chiral Magnetic Effect (CME)

\[ \langle \cos(\varphi_1 + \varphi_2 - 2\psi) \rangle \]

CME searches with
\[ <\cos(\varphi_1 + \varphi_2 - 2\psi)> \]
- Below 0 for same charges
- ~ 0 for opposite charges

Results at LHC similar to those at RHIC…

See talk from S. Voloshin for extensive experimental overview…

Non-zero correlations observed between $\psi_1$, $\psi_2$ and $\psi_3$ plane directions.
Mixed harmonics

Teaney and Yan correlator investigates $p_T$ dependence of such correlations

- Hydro with Glauber initial conditions qualitatively describes data at low $p_T$
- Data negative at high $p_T$ (in contrast to model)
Summary

1. Comprehensive set off spectra and flow measurements from ALICE
   - Strong constraints on initial conditions and global event characteristics

2. Identified particle production,
   - Radial flow 0.65c, 10% higher than RHIC,
   - Chemical freeze-out temperatures appear to have particle species dependence,
   - "Radial flow features" observed in p-Pb spectra

3. Angular correlations and flow
   - $v_2$ fluctuations appear to follow Bessel Gaussian form
   - Correlation observed between $v_2$ and spectra shapes
   - Non zero correlations observed between $\psi_1$, $\psi_2$ and $\psi_3$ planes