Soft physics in ALICE

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LHC Heavy-Ion running

• Two heavy-ion runs at the LHC so far:
  • in 2010 – commissioning and the first data taking
  • in 2011 – already above nominal instant luminosity!

• p–Pb run moved to beginning of 2013
  • jan-mar 2013 - 30 nb\(^{-1}\)
  • (for rare-probe statistics equivalent to ~0.15 nb\(^{-1}\) of Pb–Pb)

• Followed in 2013 by Long Shutdown–1 (LS1)

<table>
<thead>
<tr>
<th>year</th>
<th>system</th>
<th>energy (\sqrt{s}_{NN}) TeV</th>
<th>integrated luminosity</th>
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</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>
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Study strongly interacting matter under extreme conditions of temperature and energy densities in events of extreme particle multiplicity.

Fully characterize the events
Challenge for the experiment
Detector

Central Barrel
2 π tracking & PID
|η| < 1

Detector:
- Length: 26 meters
- Height: 16 meters
- Weight: 10,000 tons

Collaboration:
- > 1000 Members
- > 100 Institutes
- > 30 countries

ACORDE (cosmics)
V0 scintillator centrality
η: -1.7− -3.7, 2.8–5.1
T0 (timing)
ZDC (centrality)
FMD (N_{ch} -3.4<|η|<5)
PMD (N_γ, N_{ch})

Muon Spectrometer
-2.5 > η > -4
ALICE – dedicated heavy-ion experiment at the LHC

- particle identification (practically all known techniques)
- extremely low-mass tracker ~ 10% of $X_0$
- excellent vertexing capability
- efficient low-momentum tracking – down to ~ 100 MeV/c
Charged particle multiplicity

First day measurements which can exclude models

Interplay of soft and hard process
Volume and lifetime of the source

Volume at freeze out: ~ 5000 fm$^3$

x2 of RHIC

Initial volume ~ 800 fm$^3$

Lifetime from collision to freeze out

~ 10 fm/c

30% longer

Hotter, bigger and longer-lived
Identified-particle $p_T$ spectra up to 20 GeV/c

95% of all particles below 1.5 GeV/c: particle production a non-perturbative process

- **Low-$p_T < 2$ GeV/c**: dynamics of bulk matter described by Relativistic HydroDynamic Models (RHDM)
- **High-$p_T > 8$ GeV/c**: spectra reflect interaction of partons from hard scatterings with the medium
- **Intermediate $p_T \ 2 < p_T < 8$ GeV/c**: interplay of soft and hard processes
Collective expansion

\( \rho_T \) spectra and azimuthal correlations (\( v_n \))

In a thermalized system the radial expansion is driven by the pressure gradient from inside to outside resulting in boosted \( \rho_T \) spectra and decrease in HBT size.

If the system is asymmetric in spatial coordinates the expansion will lead to anisotropy in momentum space (\( v_2 \) - azimuthal correlations).

The final state anisotropy at low \( \rho_T \) is calculated using hydrodynamics, taking as input:

- initial conditions (eccentricity, volume, energy density,..)
- properties of produced matter (viscosity, ...)

- \( v_2 \) at low \( \rho_T \): collective bulk phenomena, degree of thermalization
- \( v_2 \) at high \( \rho_T \): path-length dependence of energy loss
Low $p_T$ particle production

Shape of the low-$p_T$ spectra well described by modern hydrodynamic models (3D, with viscosity, resonances included, sometimes coupled to hadronic cascade codes), similarly to collisions at lower energies.

Overall normalization of each spectrum can be modified independently in simple “blast-wave” models, but in full hydrodynamics they are tied by the “statistical” temperature.
Strange particle spectra

Strange particle spectra

Pb-Pb at $s_{NN}=2.76$ TeV, $|y|<0.5$

\[ 1/N_{\text{evs}} d^2N/dp_T dy \]

Centrality:
- 0-10 $\%$, $\times 4.0$
- 10-20 $\%$, $\times 2.0$
- 20-40 $\%$, $\times 1.5$
- 40-60 $\%$
- 60-80 $\%$
- systematic uncertainty

K$^0_S$

Pb-Pb at $s_{NN}=2.76$ TeV, $|y|<0.5$

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- 60-80 $\%$
- systematic uncertainty

$\Lambda$

Pb-Pb at $s_{NN}=2.76$ TeV

\[ 1/N_{\text{evs}} dN/dp_T \]

Centrality:
- 0-20 $\%$
- 20-40 $\%$
- 40-60 $\%$
- 60-90 $\%$

error = $\sqrt{\text{stat}^2 + \text{sys}^2}$

$\Xi^-$

Pb-Pb at $s_{NN}=2.76$ TeV

\[ 1/N_{\text{evs}} dN/dp_T \]

Centrality:
- 0-20 $\%$
- 20-40 $\%$
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$\Omega^-$

Pb-Pb at $s_{NN}=2.76$ TeV

\[ 1/N_{\text{evs}} dN/dp_T \]

Centrality:
- 0-20 $\%$
- 20-40 $\%$
- 40-60 $\%$
- 60-90 $\%$

error = $\sqrt{\text{stat}^2 + \text{sys}^2}$
Hadron yields vs. statistical model

Predicted temperature $T=164$ MeV
A. Andronic, P. Braun-Munzinger, J. Stachel NP A772 167
Thermal fit (w/o res.): $T=152$ MeV ($\chi^2/\text{ndf} = 40/9$)
$\Xi$ and $\Omega$ significantly higher than 152, agree with 164

$p/\pi$ and $\Lambda/\pi$ ratios at LHC lower than at RHIC
Hadronic re-interactions?
F. Becattini et al. 1201.6349 J. Steinheimer et al. 1203.5302
Quantum statistics leads to enhancement of identical bosons emitted close-by in phase space which modifies the 2-particle correlation function. CF relates via Fourier transformation to the space-time distribution of the source. Used in particle physics to measure source space-time size with pions (Goldhaber, Kopylov & Podgoretsky).

Transverse radii show decrease of apparent size with increasing transverse momentum. Qualitatively consistent with hydrodynamic predictions.

Radii increase with final-state multiplicity.
Coherence in pion emission

- 3-pion correlations sensitive to “chaoticity” of pion emission
- The $r_3$ cumulant should approach 2 for the “fully chaotic” limit
- At low momentum limit not reached. Possible interpretation: 10-20% coherent pion emission
- At high momentum “fully chaotic” limit reached

Radii scaling with multiplicity

- HBT radii scale roughly linearly with multiplicity $^{1/3}$ with different slopes in pp and Pb-Pb

- HBT radii in Pb-Pb vs. trend from lower energy AA:
  - $R_{\text{long}}$: perfectly agree
  - $R_{\text{side}}$: reasonably agree
  - $R_{\text{out}}$: clearly below the trend

- Behaviour of all 3 radii in qualitative agreement with hydro expectations
  - $R_{\text{out}}/R_{\text{side}}$ decreases with $\sqrt{s}$ due to change of the freeze-out shape
In baryon-antibaryon systems the dominating source of correlation is the strong Final State Interaction. The FSI has contribution from annihilation.

Strong FSI (with annihilation) can be considered in two regimes:
- low relative momentum – leads to femtosopic (anti-)correlation
- large relative momentum – leads to yield decrease via annihilation

If annihilation is responsible for lower proton yield – it should also be seen in correlations

Wide anti-correlation, consistent with annihilation effects, is observed for all baryon-antibaryon systems
$v_2$ for $\pi$, $p$, $K^\pm$, $K^0_s$, $\Lambda$, $\phi$ (not shown for $\Xi$, $\Omega$)

$\phi$ at low $p_T$ (<3 GeV/c) follows mass hierarchy
– at higher $p_T$ joins mesons

overall qualitative agreement with hydro up to $p_T$ 1.5–3 GeV/c ($\pi$–p); quantitative precision needs improvements – hadronic afterburner

$n_q (m_T)$-scaling worse than at RHIC

$n_q (p_T)$-scaling at $p_T > 1.2$ GeV/c violation 10–20%
$v_2$ shows mass ordering up to multi-strange baryons

$v_2$ vs. $p_T$ described by hydrodynamical models
Higher harmonics and initial state

- Initial geometry not described by the ideal almond shape
  - Fluctuations of initial energy/pressure distributions lead to “irregular” shapes that fluctuate event-by-event
  - Higher (odd) harmonics each one having its own symmetry plane

- Higher harmonics more sensitive to the value of shear viscosity

Hydro simulation of initial state (ideal and viscous hydro): fluctuations of initial state are damped by viscosity
$v_2$, $v_3$, $v_4$ versus $p_T$

$\nu_n$ measurements up to 20 GeV/c – where dominated by jet quenching
Non-flow effects suppressed by rapidity gap or using higher cumulants
Non-zero value of $v_2$ at high $p_T$ both for $\Delta \eta > 2$ and 4-particle cumulant

$v_3$ and $v_4$ diminish above 10 GeV/c – indication of decrease of fluctuations at high $p_T$
Fluctuations contribution to $v_2$

$v_2$ dominated by fluctuations at small eccentricity

Fluctuations independent of $p_T$
Identified particles at intermediate $p_T$

- charged particles
- different centralities for identified particles

$\pi^+ + \pi^-$

Identified particles at intermediate $p_T$

$\bullet$ different centralities for identified particles

$p + p$

$0-5\%$ Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV

$5-10\%$ Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV

$10-20\%$ Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV

$20-40\%$ Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV

$40-60\%$ Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV

$60-80\%$ Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV

$R_{AA}^{\pi}$, $R_{AA}^{h\pm}$, $R_{AA}^{K}$, $R_{AA}^{p}$

$p_T < 7$ GeV/c: $R_{AA}^{\pi} < R_{AA}^{h\pm} \sim R_{AA}^{K} < R_{AA}^{p}$; $p_T > 7$ GeV/c: all same

Adam Kisiel (WUT)

Kielce, 14 Dec 2013
Baryon-to-meson ratio: $p/\pi$

$p/\pi$ ratio at $p_T \approx 3$ GeV/c in 0–5% central Pb–Pb collisions factor ~ 3 higher than in pp at $p_T$ above ~ 10 GeV/c back to the “normal” pp value

Recombination – radial flow?

R.J.Fries et al., PRL 90 202303; PR C68 044902
Baryon-to-meson ratio: $\Lambda/K^0_S$

Baryon enhancement at LHC
- larger than at RHIC
- extending to higher $p_T$
- well described by models like EPOS

Effect of radial flow?
- extends farther than expected from radial flow

OR

Recombination of quarks?

\[
p_T(qq) \approx 2 \times p_T(q)
\]
\[
p_T(qqq) \approx 3 \times p_T(q)
\]
\[ \frac{dN_{ch}}{d\eta} \text{ in p-Pb collisions} \]

**NSD p-Pb at 5.02 TeV \ |\eta| < 2**

\[ dN_{ch}/d\eta : 16.95 \pm 0.75 \]

**Disentangle**
- final state effects: hot QCD matter
- initial state effects: cold nuclear matter

**Probe nuclear wave-function at small x**

**QCD at high gluon density:**
parton shadowing, gluon saturation?

- Models that include shadowing or saturation approximately get right value

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$\frac{dN_{\text{ch}}}{d\eta}$ energy dependence

**p-Pb**: $\sim \sqrt{s_{NN}}^{0.10}$
$dN_{\text{ch}} / d\eta : 16.95 \pm 0.75$

**pp**: $\sim \sqrt{s_{NN}}^{0.11}$
$dN_{\text{ch}} / d\eta : 6.01 \pm 0.01 \text{ (stat.)} + 0.2 - 0.12$

**Pb-Pb**: $\sim \sqrt{s_{NN}}^{0.15}$ (most central)
$dN_{\text{ch}} / d\eta : 1584 \pm 4 \text{ (stat.)} \pm 76 \text{ (syst.)}$

**p-Pb**
- 20% lower than pp, same energy
- 80% higher than dAu, 200 GeV/c
Long range correlations in p-Pb

Correlations between a trigger and an associated particle

Near-side jet
($\Delta \varphi \sim 0$, $\Delta \eta \sim 0$)

Away-side jet
($\Delta \varphi \sim \pi$, elongated in $\Delta \eta$)

Near-side ridge
($\Delta \varphi \sim 0$, elongated in $\Delta \eta$)

Can we separate the jet and ridge components?

No ridge seen in 60-100% and similar to pp
→ what remains if we subtract 60-100%?

2 < $p_T^{\text{trig}}$ < 4 GeV/c
1 < $p_T^{\text{assoc}}$ < 2 GeV/c
20% highest multiplicity class

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The double ridge

Excess in the correlation yield between the two multiplicity event classes

Fit allows to extract $v_n$ coefficient

Two ridges:
Magnitude the same and fairly flat in $\Delta \eta$

$$v_n = \sqrt{\frac{a_n}{b}}$$
Comparison to models

3+1 viscous hydro in p-Pb collisions

Boxes: ALICE data for 0-20%

Near and away side yields:
- vary over a large range
- agree for each $p_T$ and event class

Common underlying processes?
Summary

- ALICE is obtaining a wealth of physics results from the first two LHC heavy-ion runs:
  - bulk, soft probes:
    - spectra, yields and particle chemistry
    - elliptic flow of identified particles
    - higher harmonics momentum anisotropy
    - femtoscopy
  - Entering the precision measurement era
  - Important new findings from the p-Pb run
    - Total particle multiplicity discriminates models
    - The “double-ridge” structure appears