The physics of heavy-ion collisions

Alexander Kalweit, *CERN*
Overview

• Three lectures (one hour each):
  – Friday, 10:30h-11:30h (Prevessin)
  – Saturday, 11:30h-12:30h (Meyrin)
  – Monday, 10:30h-11:30h (Prevessin)

• Specialized discussion sessions with heavy-ion experts in the afternoons on Friday and Monday.

• Feel free to contact me for any questions regarding the lecture: Alexander.Philipp.Kalweit@cern.ch

• Many slides, figures, and input taken from:
  Jan Fiete Grosse-Oetringhaus, Constantin Loizides, Federico Antinori, Roman Lietava
FAQ (1)

• How many bunches are in the LHC during heavy-ion operation?
  During last run typically 518.

<table>
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<tr>
<th>Run#</th>
<th>Bunches</th>
<th>Scheme</th>
<th>Fill #</th>
<th>Energy per beam</th>
<th>Intensity per bunch</th>
<th>Mu</th>
<th>B</th>
<th>B</th>
<th>B</th>
<th>A</th>
<th>BC</th>
<th>MB Interaction</th>
<th>Rate (Hz)</th>
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• What are average event sizes?
  – In pp up to 1-2 MegaByte, in Pb-Pb up to 50 MegaByte.
  – Strong online compression (raw amplitudes -> clusters [lossy], cluster position with respect to the helix).
FAQ (2)

Causes a lot of un-needed data volume
Outline and discussion leaders

• Introduction
• The QCD phase transition
• QGP thermodynamics and soft probes (Francesca)
  – Particle chemistry
  – QCD critical point and onset of de-confinement
  – (anti-)(hyper-)nuclei
  – Radial and elliptic flow
  – Small systems
• Hard scatterings (Leticia, Marta)
  – Nuclear modification factor
  – Jets
• Heavy flavor in heavy-ions
  – Open charm and beauty
  – Quarkonia
• Di-leptons

Francesca Bellini
Leticia Cunqueiro
Marta Verweij
Reminder: QGP as the asymptotic state of QCD

Quark-Gluon-Plasma (QGP): at extreme temperatures and densities quarks and gluons behave quasi-free and are not localized to individual hadrons anymore.

$$T_0 \approx \frac{1}{40} \text{eV}$$

Where is the phase transition?
→ Lattice QCD

Asymptotic freedom: free quarks & gluons

$$T \rightarrow \infty$$

Critical temperature
$$T_c \approx 156 \text{ MeV}$$

[PRD 90 094503 (2014)]

→ Are such extreme temperatures reached in the experiment? Yes..
→ Is it for all quark flavors the same? Not clear yet..
→ …
How many particles are created in such a collision?
$dN_{ch}/d\eta$ in 5.02 TeV Pb-Pb collisions at the LHC

Even at LHC energies, 95% of all particles are produced with $p_T < 2$ GeV/c in pp and Pb-Pb collisions.

Bulk particle production and the study of collective phenomena are associated with "soft" physics in the non-perturbative regime of QCD.

$\Rightarrow$ Even at LHC energies, 95% of all particles are produced with $p_T < 2$ GeV/c in pp and Pb-Pb collisions.

$\Rightarrow$ Bulk particle production and the study of collective phenomena are associated with "soft" physics in the non-perturbative regime of QCD.
**Instrumentation for heavy-ion experiments: granularity**

- In order to cope with the high density of particles, heavy-ion detectors have to be very granular (e.g. large TPC with small read-out pads).
- Track seeding typically in outer detectors (where track density is lower) and then Kalman filter propagation to the primary vertex.
Short reminder: (Pseudo-)rapidity

Always keep in mind: Rapidity and pseudo-rapidity are not the same, especially at low transverse momenta!

$$\frac{dN}{d\eta} = \sqrt{1 - \frac{m^2}{m_T^2 \cosh^2 y}} \frac{dN}{dy}$$
Collisions of heavy-ions at high energy accelerators allow the creation of several tens of thousands of hadrons (1 \(<<\) N \(<<\) 1mol) in local thermodynamic equilibrium in the laboratory.

So, we have enough particles, but are they in local thermodynamic equilibrium? How can we test that?
Collisions of heavy-iions at high energy accelerators allow the creation of several tens of thousands of hadrons ($1 \ll N \ll 1\text{mol}$) in local thermodynamic equilibrium in the laboratory. Success of hydro models describing spectral shapes and azimuthal anisotropies supports idea of matter in local thermal equilibrium (kinetic).

Success of thermal models describing yields of hadrons composed of up, down, and strange quarks supports idea of matter in local thermal equilibrium (chemical).

Equilibrium models such as hydro typically need 5-6 interactions to work. Where does this picture break down? Does it work in pp and pPb? \textbf{What is the smallest possible QGP droplet?}
A short introduction to statistical thermodynamics (1)

- The maximum entropy principle leads to the thermal most likely distribution of particle species.

- Entropy: the number of possible micro-states $\Omega$ being compatible with a macro-state for a given set of macroscopic variables $(E, V, N)$:

$$S = k_B \cdot \ln \Omega$$

- Compatibility to a given macroscopic state can be realized exactly or only in the statistical mean.
A short introduction to statistical thermodynamics (2)

- We therefore distinguish three different statistical ensembles:

  (i) micro-canonical: $E, V, N$ fix

  (ii) canonical: $T, V, N$ fix
  \[\rightarrow\] given volume element is coupled to a heat bath

  (iii) grand-canonical: $T, V, \mu$ fix
  \[\rightarrow\] given volume element can also exchange particles with its surrounding (heat bath and particle reservoir)
A short introduction to statistical thermodynamics (3)

• A small example: barometric formula (density of the atmosphere at a fixed temperature as a function of the altitude $h$).

• Probability to find a particle on a given energy level $j$:

$$P_j = \frac{\exp \left( - \frac{E_j}{k_B T} \right)}{Z}$$

Boltzmann factor

Partition function $Z$

(Zustandssumme = “sum over states”)

• Energy on a given level is simply the potential energy: $E_{\text{pot}} = mgh$. This implies for the density $n$ (pressure $p$):

$$\frac{p(h_1)}{p(h_0)} = \frac{n(h_1)}{n(h_0)} = \frac{N \cdot P(h_1)}{N \cdot P(h_0)} = \exp \left( - \frac{\Delta E_{\text{pot}}}{k_B T} \right) = \exp \left( - \frac{mg}{RT} \Delta h \right)$$
QGP thermodynamics and soft probes

Particle chemistry
Statistical-thermal model for heavy-ion collisions

- Starting point: grand-canonical partition function for an relativistic ideal quantum gas of hadrons of particle type i (i = pion, proton, ... → full PDG!):

\[ \ln Z_{GK,i} = \pm g_i \frac{V}{2\pi^2 h^3} \int_0^\infty dp \; p^2 \ln \left( 1 \pm e^{-\beta (E_i - \mu_i)} \right) \]

\[ \beta = \frac{1}{kT} \]

\[ E_i = \sqrt{p^2 + m_i^2} \]

(-) for bosons, (+) for fermions (quantum gas)

Spin degeneracy

\[ \mu_i = \mu_B B_i + \mu_S S_i + \mu_L L_i + \mu_C C_i \]

chemical potential representing each conserved quantity

- Once the partition function is known, we can calculate all other thermodynamic quantities:

\[ n = \frac{1}{V} \frac{\partial (T \ln Z)}{\partial \mu} \]

\[ P = \frac{\partial (T \ln Z)}{\partial V} \]

\[ s = \frac{1}{V} \frac{\partial (T \ln Z)}{\partial T} \]

Only two free parameters are needed: \((T, \mu_B)\). Volume cancels if particle ratios \(n_i/n_j\) are calculated. If yields are fitted, it acts as the third free parameter.

Partition function shown here is only valid in the resonance gas limit (HRG), i.e. relevant interactions are mediated via resonances, and thus the non-interacting hadron resonance gas can be used as a good approximation for an interacting hadron gas.
$p_T$-spectra of identified particles

1. Identify particle in the detector (pion, kaon, proton, Lambda, Xi, Omega, anti-deuteron…)
2. Fill $p_T$-spectrum
3. Interpolate unmeasured region at low $p_T$ (at high $p_T$ negligible)
4. Integrate:

$$\frac{dN}{dy} = \int \frac{d^3N}{dp_T dy d\phi} \ d\phi dp_T$$
Instrumentation for heavy-ion experiments: PID

In order to measure as many different particle species directly, heavy-ion experiments typically have a lot of particle identification (PID) detectors.
Chemical equilibrium at the LHC (1)

Production yields of light flavour hadrons from a chemically equilibrated fireball can be calculated by statistical-thermal models (roughly $dN/dy \sim \exp\{-m/T_{ch}\}$, in detail derived from partition function)

$\rightarrow$ In Pb-Pb collisions, particle yields of light flavor hadrons are described over 7 orders of magnitude with a common chemical freeze-out temperature of $T_{ch} \approx 156$ MeV.

$\rightarrow$ This includes strange hadrons which are rarer than $u,d$ quarks. Approx. every fourth to fifth quark (every tenth) is a strange quark in Pb-Pb collisions (in pp collisions).

$\rightarrow$ Light (anti-)nuclei are also well described despite their low binding energy ($E_b << T_{ch}$).
Particle yields of light flavor hadrons are described over 7 orders of magnitude within 20% (except K*0) with a common chemical freeze-out temperature of $T_{ch} \approx 156$ MeV (prediction from RHIC extrapolation was $\approx 164$ MeV).

Hadrons are produced in apparent chemical equilibrium in Pb-Pb collisions at LHC energies.

Largest deviations observed for protons (incomplete hadron spectrum, baryon annihilation in hadronic phase,..?) and for K*0.

Three different versions of thermal model implementations give similar results.

[Andronic et al, PLB 673 142]
Sequential freeze-out?

• Are the deviations observed in the thermal model fit for p and Ξ due to physics?

• Two main ideas on the market:

  (1.) Different chemical freeze-out temperatures for s w.r.t. to u,d quarks. → motivated by LQCD

  Similar to heating a mixture of alcohol (boiling point 78.32 °C) and water (boiling point 100 °C).

  (2.) Inelastic collisions in the hadronic phase.

  → Was this previously overlooked, because the difference is “only” about 10 MeV?

Interesting research topic for the next years.
Chemical equilibrium vs collision energy

- Hadron yields from SIS up to RHIC and LHC can be described in a hadro-chemical model applying thermal fits.

- Effective parameterization of \((T, \mu_B)\) as a function of collision energy:

\[
T[\text{MeV}] = T_{\text{lim}} \left(1 - \frac{1}{0.7 + (\exp(\sqrt{s_{NN}}(\text{GeV}) - 2.9)) / 1.5}\right)
\]

\[
\mu_B[\text{MeV}] = \frac{a}{1 + b\sqrt{s_{NN}}(\text{GeV})},
\]

- Particle ratios can be calculated (or predicted) at any collision energy.…

→ One observes a \textit{limiting temperature of hadron production} around \(T \approx 160\text{MeV}\).
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Chemical freeze-out line

- By colliding nuclei with different center of mass energies, different regions of the phase diagram are explored.

- Thermal model fits to the experimental data define the chemical freeze-out line in the QCD phase diagram.

- The previously schematic phase diagram becomes one which is actually measured.
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Chemical freeze-out as a proof of QGP existence?

A priori, a thermal model description is not related to the QGP itself. It describes a hadron gas and not a parton gas.

However, the chemical freeze-out line determined by thermal fits coincides with the phase boundary calculated by lattice QCD above top SPS energies!
Small systems: high multiplicity pp and pPb
Particle chemistry
How does hadrochemistry evolve with system size?

Low multiplicity pp
High multiplicity pp
~ as in peripheral PbPb

ALICE,
pp 7TeV
Chemical equilibrium in small systems

- Smooth evolution of hadrochemistry observed from pp to pPb to Pb-Pb collisions as a function of charged particle multiplicity.
- Significant enhancement of strange to non-strange particle production observed in pp collisions.
- pp collision data allows to compare to a plethora of QCD inspired event generators:
  - **PYTHIA8** completely misses the behavior of the data (independent of switching ON/OFF color reconnection)
  - **DIPSY** (color ropes) describes the increase in strangeness production qualitatively but fails to predict protons correctly in its original version.
  - **EPOS-LHC** (core-corona) only qualitatively describes the trend.
Chemical equilibrium in small systems

- The chemical equilibrium picture holds also in small collision systems such as high multiplicity pp and pPb collisions.

→ Currently one of the hottest topics in heavy-ion research!

→ Hyperon-to-pion enhancement is strangeness related and not mass or baryon number related.
Strangeness canonical suppression

- From a thermal-statistical point of view strangeness production is very sensitive to the system size, i.e. the total number of produced particles.

- As it is rare (w.r.t to u,d), but not so rare (w.r.t c,b,t), its thermal production rate is influenced by the explicit conservation of the strangeness quantum number.

- Simplified picture: explicit conservation of strangeness limits the phase-space for strange particle production and leads to a suppression in small systems (<- strangeness enhancement in large systems).
QGP thermodynamics and soft probes

Search for QCD critical point and onset of de-confinement
The QCD critical point

- By a variation of beam energies, one might hit the critical point in the QCD phase diagram => critical chiral dynamics.

Different regions of the phase diagram are probed with different $\sqrt{s_{NN}}$. => Beam energy scan (BES) at RHIC.
Critical fluctuations – in ordinary matter

- Phase transitions are often connected to critical phenomena.

- Example: Opalescence of Ethene at the critical point (divergence of correlation lengths).

[S. Horstmann, Ph.D. Thesis University Oldenburg]
Fluctuations in QCD

- QCD phase transitions: the thermodynamic susceptibilities $\chi$ of the conserved quantities of QCD (electric charge $Q$, baryon number $B$, Strangeness $S$) correspond to (event-by-event) fluctuations in the particle production.

$$\chi_{lmmn}^{BSQ} = \frac{\partial^{l+m+n}(P/T^4)}{\partial(\mu_B/T)^l \partial(\mu_S/T)^m \partial(\mu_S/T)^n}$$

- Fluctuations are quantified as moments (mean, variance, skewness, kurtosis) or cumulants $K$ of the event-by-event distributions:

$$M = K_1 = \mu = \langle N \rangle = VT^3 \cdot \chi_1$$
$$\sigma^2 = K_2 = \mu_2 = \langle (\delta N)^2 \rangle = VT^3 \cdot \chi_2$$
$$S = K_3/\sigma^3 = \mu_3/\sigma^3 = \langle (\delta N)^3 \rangle/\sigma^3 = VT^3 \cdot \chi_3/(VT^3 \cdot \chi_2)^{3/2}$$
$$\kappa = K_4/\sigma^4 = (\mu_4 - 3\mu_2^2)/\mu_2^2 = \langle (\delta N)^4 \rangle/\sigma^4 - 3 = (VT^3 \cdot \chi_4)/(VT^3 \cdot \chi_2)^2$$

$$\mu_i = \langle (\delta N)^i \rangle$$
$$\delta N = N - \langle N \rangle$$
Critical fluctuations – in quark matter

- In the QCD case, **event-by-event fluctuations** in the conserved charges of QCD (Baryon number $B$, Strangeness $S$, electric charge $Q$).

- Key observable: baryon number fluctuations quantified as the higher moments $\chi_B$ of the net-proton ($N_p - N_{\text{anti-p}}$) distribution $\Rightarrow$ fixed at chemical freeze-out.

$$\Rightarrow$$ Hint for deviation from Poisson baseline in kurtosis around $\sqrt{s_{NN}} \approx 20$ GeV?

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[PRL 112 (2014) 032302]
Chiral critical dynamics at LHC energies

- Even though LHC energies are far away from the critical point, remnants of the critical chiral dynamics might still be measurable in higher order net-charge fluctuations at the LHC.

→ Test of a Lattice QCD prediction.

→ Experimental proof that chiral and de-confinement phase transition occur indeed at the same temperature.

[EUR. PHYS. J. C 71 (2011) 1694]
QGP thermodynamics and soft probes (anti-)(hyper-)nuclei
Particle identification via $dE/dx$

\[
\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \beta^2 \left[ \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{\text{max}}}{I^2} - \beta^2 - \frac{\delta(\beta \gamma)}{2} \right]
\]

Separation of $z = 1$ and $z = 2$ via $dE/dx$ is also very important for the correct determination of the momentum via the track curvature: $p_T \sim 0.3 \, B \cdot r \cdot z$
Measurements of (anti-)(hyper-)nuclei

- Collisions at the LHC produce a large amount of (anti-)(hyper-)nuclei.
  - Matter and anti-matter are produced in equal abundance at LHC energies.
  - Open puzzle: production yields are in agreement with thermal model prediction even though light (anti-)nuclei should be dissolved in such a hot medium.
Table of nuclides

The diagram illustrates the distribution of nuclides based on proton number $Z$ and neutron number $N$. Key features include:

- Stable isotopes
- Radioactive decay chains
- Light particles
- Fusion/transfer
- Fragmentation
- Unknown
- Predicted driplines

Notable points include:

- $Z=82$
- $N=184$
- $N=258$
- $N=50$
- $N=82$
- $N=28$
- $Z=50$
- $Z=28$

This visual representation helps in understanding the stability and decay patterns of nuclides across different neutron-to-proton ratios.
Light (anti-)nuclei

- Even in Pb-Pb collisions at LHC energies, light anti-nuclei are rarely produced.

- (Anti-)nuclei up to the (anti-)alpha are in reach (1st observation of the anti-alpha by the STAR experiment at RHIC in 2011).

→ A very good and very stable particle identification is needed to separate these rare particles from the background.
Testing CPT with anti-nuclei

The ALICE collaboration performed a test of the CPT invariance looking at the mass difference between nuclei and anti-nuclei.

This test shows that the masses of nuclei and anti-nuclei are compatible within the uncertainties. The binding energies are compatible in nuclei and anti-nuclei as well.

Mass ordering

→ For each additional nucleon the production yield decreases by a factor of about 300!

→ Such a behaviour can be directly derived from the thermal model which predicts in first order $dN/dy \sim \exp(-m/T)$.
Hyper-nuclei (1)

• By ‘replacing’ one nucleon by one hyperon, the table of nuclides can be extended in a third dimension.
• Hyper-nuclei have a long tradition in nuclear physics: discovery in the 1950s by M. Danysz and J. Pniewski in a nuclear emulsion exposed to cosmic rays.
Hyper-nuclei (2)

• Reconstruction of hyper-nuclei can be based on well established techniques for $\Lambda$ and other weakly decaying light flavor hadrons as lifetimes and decay topologies are similar.

\[ \Lambda \rightarrow p + \pi^- \ (63.9\%) \]

• Experimentally one searches for (anti-)nuclei from displaced vertices:

\[
\begin{align*}
^{3}\Lambda H & \rightarrow ^{3}He + \pi^- \\
^{3}\Lambda H & \rightarrow d + p + \pi^- \\
^{4}\Lambda H & \rightarrow ^{4}He + \pi^- \\
^{4}\Lambda He & \rightarrow ^{3}He + p + \pi^- \\
^{5}\Lambda He & \rightarrow ^{4}He + p + \pi^- 
\end{align*}
\]

• Branching ratios are only partially constrained by measurements.
(anti-) (hyper-) nuclei – impact beyond heavy-ion physics

A. Heavy-ion measurements may help in constraining the not well known lifetime of the hyper-triton (sensitive to the hyperon-nucleon interaction potential in nuclear physics).

B. Collider measurements are used for background estimations in the searches for (anti-) nuclei of galactic/dark matter origin (such as in AMS).

[K. Blum et al., arXiv:1704.05431]
QGP thermodynamics and soft probes
Radial and elliptic flow
Bulk particle production and collectivity

- Low $p_T$ hadrons composed of (u,d,s) valence quarks define the collective behaviour of the fireball.

- “Baseline model of ultra-relativistic heavy-ion physics”

A fireball in local thermodynamic equilibrium:

- Particle chemistry in agreement with thermal model predictions
- $p_T$-spectra and $v_2$ measurements show patterns of radial and elliptic hydrodynamic flow.

N.B.: Collective flow has nothing to do with the particle flow method to reconstruct tracks and jets in ATLAS/CMS
Radial and elliptic flow

Isotropic radial flow

Anisotropic (elliptic) flow

Spatial deformation

Azimuthal (φ) pressure gradients

Anisotropic particle density

\[ \frac{dN}{d\phi} \propto 1 + 2v_1 \cos[\phi - \Psi_1] + 2v_2 \cos[2(\phi - \Psi_2)] + 2v_3 \cos[3(\phi - \Psi_3)] + \ldots \]
Flow in AA collisions

- Flow picture: Collective motion of particles superimposed to the thermal motion.
- Radial flow is a natural consequence of any interacting system expanding into the vacuum.

From: C. Loizides

Radial flow first mentioned: Shuryak, PLB 89 (1980) 253
Common radial hydrodynamic expansion leads to a modification of the spectral shape: mass dependent *boost*.

- $p_T$-spectra harden with centrality.
- More pronounced for heavier particles (e.g.: $p > K > \pi$) as *velocities* become equalized in the flow field ($p = \beta \gamma \cdot m$).
- Hydrodynamic models show a good agreement with the data.
Radial flow (2)

Common radial hydrodynamic expansion leads to a modification of the spectral shape: mass dependent boost.

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Radial flow (3)

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Blast-wave model (1)

• How fast is the expansion velocity? Estimate in a simplified hydro model:
  – Consider a thermal source (Boltzmann type $p_T$-spectrum) of particles:
    \[ E \frac{d^3N}{dp^3} \propto E e^{-E/T} \quad E = m_T \cosh(y) \]
  – Boost source radially with velocity $\beta$ and evaluate at $y=0$:
    \[
    \frac{1}{m_T} \frac{dN}{dm_T} = m_T I_0 \left( \frac{p_T \sinh(\rho)}{T} \right) K_1 \left( \frac{m_T \cosh(\rho)}{T} \right) \quad \rho = \tanh^{-1}(\beta)
    \]
  – Simple assumption: consider uniform sphere of radius $R$
    \[
    \frac{1}{m_T} \frac{dN}{dm_T} \propto \int_0^R r \, dr \, m_T I_0 \left( \frac{p_T \sinh(\rho(r))}{T} \right) K_1 \left( \frac{m_T \cosh(\rho(r))}{T} \right)
    \]
    and parameterize velocity profile as \( \beta(r) = \beta_S (r/R)^n \)

• Three free parameters: kinetic freeze-out temperature $T_{\text{kin}}$, surface expansion velocity $\beta_S$, exponent $n$ of velocity profile.
Blast-wave model (2)

- Common blast-wave fit gives a good description of the data at low transverse momenta.
- Average expansion velocity: \( \sim 0.65c \)
- Kinetic freeze-out temperature: \( \sim 80 \text{ MeV} \)
End of lecture 2

• Now we know the temperature of the system at the final decoupling.
• Tomorrow: elliptic flow and why the QGP is an *ideal liquid*.

Particle detection
(t≈$10^{15}$fm/c)

Kinetic freeze-out
(t=10fm/c)

Chemical freeze-out

Hydrodynamic evolution (t~0.5fm/c)

Pre-equilibrium
Collision (t=0fm/c)
Small systems: high multiplicity pp and pPb
Radial and elliptic flow
Hydrodynamic expansion – spectral shapes and

Textbook-like hardening of $p_T$-spectra as expected in hydro:

- With centrality
- With the particle mass: $p = \beta \gamma \cdot m$

$\rightarrow$ Initial spatial anisotropy is converted by scatterings into an anisotropy in momentum space.
Elliptic flow (heavy-ion physics)

[PRL 116, 132302 (2016)]

\[ V_2 \]

![Graph showing elliptic flow](ALI-PUB-105802)
Elliptic flow (ALICE)

Validity of hydrodynamic description confirmed at the highest centre-of-mass energies available.

Expected mass ordering $(p = \beta \gamma \cdot m)$ observed.
(Double) ridges

- Long-range azimuthal correlations (as originating from elliptic flow) are also observed in small systems: double ridges.

- Similar observations hold true for many other typical \textit{kinetic heavy-ion} observables measured in high multiplicity pp and pPb collisions $\rightarrow$ clear indication for collectivity in small systems.