Physics perspectives with heavy ions at the High Luminosity - LHC and beyond

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Heavy ions at the HL-LHC

Ongoing discussion, see for example:

- Jan-Fiete Grosse-Oetringhaus, talk at Workshop on the physics of HL-LHC, 30.10.2017: https://indico.cern.ch/event/647676/timetable/
- Andrea Dainese, talk at ECFA High Luminosity LHC Experiments Workshop, 04.10.2016: https://indico.cern.ch/event/524795/timetable/
- Antonio Uras, Heavy-Ions at the High-Luminosity LHC: http://inspirehep.net/record/1589642
- preparation of a CERN yellow report chapter on Heavy ions at the HL-LHC, working group meeting: https://indico.cern.ch/event/717641/
- existing CERN yellow report chapter on Heavy Ions at the Future Circular Collider: http://inspirehep.net/record/1455787?ln=de

I will not attempt to reflect the full ongoing discussion, but rather present my own point of view (as a theorist).
Little bangs in the laboratory
A great challenge

- quantum fields at finite energy density and temperature
- fundamental gauge theory: QCD
- strongly interacting
- non-equilibrium dynamics
- experimentally driven field of research
- big motivation for theory development
Fluid dynamics

- long distances, long times or strong enough interactions
- matter or quantum fields form a fluid!
- needs **macroscopic** fluid properties
  - thermodynamic equation of state $p(T, \mu)$
  - shear viscosity $\eta(T, \mu)$
  - bulk viscosity $\zeta(T, \mu)$
  - heat conductivity $\kappa(T, \mu)$
  - relaxation times, ...

- *ab initio* calculation of fluid properties difficult but fixed by **microscopic** properties in $\mathcal{L}_{\text{QCD}}$
Relativistic fluid dynamics

**Energy-momentum tensor** and conserved current

\[ T^{\mu\nu} = \epsilon u^\mu u^\nu + (p + \pi_{\text{bulk}}) \Delta^{\mu\nu} + \pi^{\mu\nu} \]

\[ N^\mu = n u^\mu + \nu^\mu \]

- tensor decomposition using fluid velocity \( u^\mu \), \( \Delta^{\mu\nu} = g^{\mu\nu} + u^\mu u^\nu \)
- thermodynamic equation of state \( p = p(T, \mu) \)

Covariant **conservation laws** \( \nabla_\mu T^{\mu\nu} = 0 \) and \( \nabla_\mu N^\mu = 0 \) imply

- equation for **energy density** \( \epsilon \)

\[ u^\mu \partial_\mu \epsilon + (\epsilon + p + \pi_{\text{bulk}}) \nabla_\mu u^\mu + \pi^{\mu\nu} \nabla_\mu u_\nu = 0 \]

- equation for **fluid velocity** \( u^\mu \)

\[ (\epsilon + p + \pi_{\text{bulk}}) u^\mu \nabla_\mu u^\nu + \Delta^{\nu\mu} \partial_\mu (p + \pi_{\text{bulk}}) + \Delta^{\nu\alpha} \nabla_\mu \pi^{\mu\alpha} = 0 \]

- equation for **particle number density** \( n \)

\[ u^\mu \partial_\mu n + n \nabla_\mu u^\mu + \nabla_\mu \nu^\mu = 0 \]
Constitutive relations

Second order relativistic fluid dynamics:

- equation for **shear stress** $\pi^{\mu\nu}$

$$
\tau_{\text{shear}} P^{\rho\sigma}_{\alpha\beta} u^\mu \nabla_\mu \pi^{\alpha\beta}_{\rho\sigma} + \pi^{\rho\sigma} + 2\eta P^{\rho\sigma}_{\alpha\beta} \nabla_\alpha u^\beta + \ldots = 0
$$

with **shear viscosity** $\eta(T, \mu)$

- equation for **bulk viscous pressure** $\pi_{\text{bulk}}$

$$
\tau_{\text{bulk}} u^\mu \partial_\mu \pi_{\text{bulk}} + \pi_{\text{bulk}} + \zeta \nabla_\mu u^\mu + \ldots = 0
$$

with **bulk viscosity** $\zeta(T, \mu)$

- equation for **baryon diffusion current** $\nu^\mu$

$$
\tau_{\text{heat}} \Delta^{\alpha}_{\beta} u^\mu \nabla_\mu \nu^\beta + \nu^\alpha + \kappa \left[ \frac{nT}{\epsilon + p} \right]^2 \Delta^{\alpha\beta} \partial_\beta \left( \frac{\mu}{T} \right) + \ldots = 0
$$

with **heat conductivity** $\kappa(T, \mu)$
Thermodynamics of QCD

- thermodynamic equation of state $p(T)$ rather well understood now
- also moments of conserved charges like

$$\chi_2^B = \frac{\langle (N_B - N_{\bar{B}})^2 \rangle}{VT^3}$$

and higher order understood
- progress in computing power
Quantum fields and information

- surprising relations between quantum field theory and information theory
- well understood in thermal equilibrium
- currently investigated out-of-equilibrium
- fluid dynamics / entanglement entropy / black hole physics (AdS/CFT)
- shear viscosity to entropy density ratio $\eta/s \geq \hbar/(4\pi k_B)$
  
  [Kovtun, Son, Starinets (2003)]

Figure 3: The holographic calculation of entanglement entropy via AdS/CFT.

the deficit angle $\delta$ localized on a codimension two surface $\gamma$. This is clearly true in the three-dimensional pure gravity as the solution to the Einstein equation should be locally the same as AdS$_3$. However, this is not trivially obvious in higher dimensions. Under this assumption, the Ricci scalar behaves like a delta function $R = 4\pi (1 - n) \delta(\gamma_A) + R(0)$, (3.4)

where $\delta(\gamma_A)$ is the delta function localized on $\gamma_A$, $\delta(\gamma_A) = \infty$ for $x \in \gamma_A$ whereas $\delta(\gamma_A) = 0$ otherwise, and $R(0)$ is that of the pure AdS$_{d+2}$. Then we plug this in the supergravity action

$$S_{AdS} = -\frac{1}{16\pi G} (d+2)N \int M dx^{d+2} \sqrt{|g|} (R + \Lambda) + \cdots,$$

(3.5)

where we only make explicit the bulk Einstein-Hilbert action. This is because the other parts omitted in the above such as kinetic terms of scalars lead to extensive terms which are proportional to $n$ and are canceled in the ratio (2.20). Now the bulk to boundary relation (3.2) equates the partition function of CFT with the one of AdS gravity. Thus we can holographically calculate the entanglement entropy $S_A$ as follows

$$S_A = -\frac{\partial}{\partial n} \log \text{Tr} \rho_n^A |_{n=1} = -\frac{\partial}{\partial n} \left[ (1 - n) \text{Area}(\gamma_A) \right] \frac{4}{G} \frac{d+2}{N} = \text{Area}(\gamma_A) \frac{4}{G} \frac{d+2}{N}.$$  

(3.6)

The action principle in the gravity theory requires that $\gamma_A$ is the minimal area surface. In this way, we reproduced our holographic formula (3.3) [27]. Notice that the presence of non-trivial minimal surfaces is a well-established property of asymptotically AdS spaces.

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QCD strings and entanglement

[ Berges, Floerchinger, Venugopalan (2017) ]

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Characterization by entanglement entropy $S_A = \text{Tr} A \{ \rho_A \ln(\rho_A) \}$ could this lead to thermal-like effects? 

[Ryu, Takayanagi (2006) ]

[ Berges, Floerchinger, Venugopalan (2017) ]
Non-central collisions

- pressure gradients larger in reaction plane
- leads to larger fluid velocity in this direction
- more particles fly in this direction
- can be quantified in terms of elliptic flow $v_2$
- particle distribution

\[
\frac{dN}{d\phi} = \frac{N}{2\pi} \left[ 1 + 2 \sum_m v_m \cos(m(\psi - \phi_R)) \right]
\]

- symmetry $\phi \rightarrow \phi + \pi$ implies $v_1 = v_3 = v_5 = \ldots = 0$. 
Two-particle correlation function

- normalized two-particle correlation function

\[ C(\phi_1, \phi_2) = \frac{\langle \frac{dN}{d\phi_1} \frac{dN}{d\phi_2} \rangle_{\text{events}}}{\langle \frac{dN}{d\phi_1} \rangle_{\text{events}} \langle \frac{dN}{d\phi_2} \rangle_{\text{events}}} = 1 + 2 \sum_m v_m^2 \cos(m(\phi_1 - \phi_2)) \]

- surprisingly \( v_2, v_3, v_4, v_5 \) and \( v_6 \) are all non-zero!

[ALICE 2011, similar results from CMS, ATLAS, Phenix, Star]
Event-by-event fluctuations

- deviations from symmetric initial energy density distribution from event-by-event fluctuations
- one example is Glauber model
**Big bang – little bang analogy**

- cosmological scale: \( \text{Mpc} = 3.1 \times 10^{22} \text{ m} \)
- Gravity + QED + Dark sector
- one big event

- nuclear scale: \( \text{fm} = 10^{-15} \text{ m} \)
- QCD
- very many events

- initial conditions not directly accessible
- all information must be reconstructed from final state
- dynamical description as a fluid
- fluctuating initial state
Similarities to cosmological fluctuation analysis

- fluctuation spectrum contains info from early times
- detailed correlation functions are compared to theory
- can lead to detailed understanding of evolution
- Mode-by-mode fluid dynamics for heavy ion collisions

[Floerchinger, Wiedemann (2014)]
The dark matter fluid

- **high energy nuclear collisions**
  \[ \mathcal{L}_{\text{QCD}} \rightarrow \text{fluid properties} \]

- **late time cosmology**
  \[ \text{fluid properties} \rightarrow \mathcal{L}_{\text{dark matter}} \]

- until direct detection of dark matter it can only be observed via gravity
  \[ G^{\mu\nu} = 8\pi G_N \ T^{\mu\nu} \]
  so all we can access is
  \[ T^{\mu\nu}_{\text{dark matter}} \]

- strong motivation to study heavy ion collisions and cosmology together!
Collective behavior in large and small systems

- Flow coefficients from higher order cumulants $v_2\{n\}$ agree:
  → collective behavior
- Elliptic flow signals also in pPb and pp!
- Can fluid approximation work for pp collisions?
Questions and puzzles

- how universal are collective flow and fluid dynamics?
  - as a limit of kinetic theory / perturbation theory / multi-parton interactions
  - non-perturbative understanding / entanglement
- what determines density distribution of a proton?
  - constituent quarks or interacting gluon cloud?
  - generalized PDFs
- more elementary collision systems? [News at Quark Matter 2018!]

- role of electromagnetic fields and vorticity for fluid dynamics
- role of quantum anomalies (e. g. chiral magnetic effect)
Chemical freeze-out

[Andronic, Braun-Munzinger, Redlich, Stachel (2017)]

- chemical freeze-out close to chiral crossover transition for large $\sqrt{s}$
- chiral transition should be visible in higher moments $\langle (N_B - N_{\bar{B}})^n \rangle$
- traces of the evolving chiral condensate / pion condensate?
- more insights at large $\mu_B$ expected from FAIR
Quarkonium and how it gets modified

- all $\Upsilon$ states are suppressed by medium effects, excited states even more
- more detailed understanding of heavy quark bound states in a medium
- also at LHC: regeneration and flow of charmed mesons
- future: also bottom
Jet quenching

- asymmetry between reconstructed jet energies
  \[ A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \quad \Delta \phi > \pi/2 \]

- partons/jets lose energy to the quark gluon plasma
- jet structure can be investigated in detail
- more possible: \( b \)-jets, \( t \)-jets
- interplay of microscopic partons / jets and macroscopic QCD fluid
Light-by-light scattering

[ATLAS, Nature Phys. 13, 852 (2017)]

- ultra-peripheral ion collisions produce strong electromagnetic fields
- beam of quasi-real photons (equivalent photon approximation)
- Halpern scattering $\gamma \gamma \rightarrow \gamma \gamma$ observed, more detailed studies possible
- also ultra-peripheral: nuclear PDFs
Theory development

- many interesting experimental results available or in reach
- precise studies need interplay of theory and experiment
- **more dedicated theory development needed**
- **we need to develop and maintain a standard model**
- heavy ion collisions and QCD dynamics can be understood much better!
Plans for heavy ions at runs 2-4 at the LHC

[J.-F. Grosse-Oetringhaus, CERN, 30.10.2017]

- Run 2:
  - Pb-Pb: few nb\(^{-1}\) (0.7 nb\(^{-1}\) in 2015, ~1 nb\(^{-1}\) in 2018) at \(\sqrt{s_{NN}} = 5\) TeV
  - p-Pb at 5 and 8 TeV (185 nb\(^{-1}\) in 2016)
  - pp reference at Pb-Pb energy (5 TeV, Nov 2017)

- LS2:
  - LHC injector upgrades; bunch spacing reduced to 50 ns
  - Pb-Pb interaction rate up to 50 kHz (now <10 kHz)
  - Experiments’ upgrades (also LS3)

- Runs 3+4:
  - Request for Pb-Pb: >10 nb\(^{-1}\)
    (ALICE: 10 nb\(^{-1}\) at 0.5T + 3 nb\(^{-1}\) at 0.2T)
  - In line with projections by machine: 3.1 nb\(^{-1}\)/month (Chamonix 2017)

HL-LHC for heavy ions begins in Run 3!
Foreseen detector upgrades

[J.-F. Grosse-Oetringhaus, CERN, 30.10.2017]

Detector Upgrades
most relevant to heavy-ion physics

• ALICE (LS2)
  – New inner tracker: precision and efficiency at low $p_T$
  – New pixel forward muon tracker: precise tracking and vertexing for $\mu$
  – TPC upgrade + readout + online data reduction $\times 100$ faster readout (continuous)

• ATLAS (LS2/LS3)
  – Fast tracking trigger (LS2): high-multiplicity tracking
  – Calorimeter and muon upgrades (LS2): electron, $\gamma$, muon triggers
  – ZDC replacement planned (LS2): radiation hardness, granularity
  – Completely new tracker (LS3): tracking and b-tag up to $\eta=4$

• CMS (mainly LS3)
  – Extension of forward muon system (LS2): muon acceptance
  – Completely new tracker (LS3): tracking and b-tag up to $\eta=4$
  – Upgrade forward calorimeter (LS3): forward jets in HI

• LHCb (LS2)
  – Triggerless readout, full software trigger, higher granularity detectors: impact on tracking performance in Pb-Pb being studied
  – Fixed-target programme with SMOG + possible extensions
Higher energies

[Dainese, Wiedemann (ed.) et al. (2017)]

Table 2: Global properties measured in central Pb–Pb collisions (0–5% centrality class) at \( p_{\text{SNN}} = 2.76 \) TeV and extrapolated to 5.5 and 39 TeV. The measurements at 2.76 TeV are reported for comparison only and without experimental uncertainties.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Pb–Pb 2.76 TeV</th>
<th>Pb–Pb 5.5 TeV</th>
<th>Pb–Pb 39 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{dN_{\text{ch}}}{d\eta} ) at ( \eta = 0 )</td>
<td>1600</td>
<td>2000</td>
<td>3600</td>
</tr>
<tr>
<td>Total ( N_{\text{ch}} )</td>
<td>17000</td>
<td>23000</td>
<td>50000</td>
</tr>
<tr>
<td>( \frac{dE_T}{d\eta} ) at ( \eta = 0 )</td>
<td>1.8–2.0 TeV</td>
<td>2.3–2.6 TeV</td>
<td>5.2–5.8 TeV</td>
</tr>
<tr>
<td>Homogeneity volume</td>
<td>5000 fm(^3)</td>
<td>6200 fm(^3)</td>
<td>11000 fm(^3)</td>
</tr>
<tr>
<td>Decoupling time</td>
<td>10 fm/c</td>
<td>11 fm/c</td>
<td>13 fm/c</td>
</tr>
<tr>
<td>( \varepsilon ) at ( \tau = 1 \text{ fm/c} )</td>
<td>12–13 GeV/fm(^3)</td>
<td>16–17 GeV/fm(^3)</td>
<td>35–40 GeV/fm(^3)</td>
</tr>
</tbody>
</table>

Larger collision energy

- higher initial energy density and temperature
- higher multiplicity \( N_{\text{ch}} \)
- larger lifetime and volume of fireball
- better probes of collective physics
- thermal charm quarks
- more hard probes
A dedicated detector for low $p_T$?

- advances in detector technology might allow to construct dedicated detector for low $p_T$ spectrum
- down to $p_T \approx 10$ MeV $\approx \frac{1}{20}$ fm?
- low momentum di-leptons
  - excellent understanding of charmonia and bottomonia (P-wave)
- probe macroscopic properties of QCD fluid: very soft pions, kaons, protons, di-leptons
  - dynamics of chiral symmetry restoration
  - pion condensates / disoriented chiral condensates?
- understand thermalization and dissipation in detail
  - spectrum also at $p_T \ll T_{\text{kinetic freeze-out}} \approx 120$ MeV
Conclusions

- high energy nuclear collisions produce a relativistic QCD fluid!
- interesting parallels between cosmology and heavy ion collisions
- heavy ion collisions provide chance to understand a relativistic fluid from first principles
- experimental hints for collective flow also in pPb and pp collisions
- QCD fluid can be understood in much more detail with combined effort of theory and experiment!
- *I had to skip many interesting topics, please see also other presentations mentioned on the first slide.*