Physics perspectives with heavy ions at the High Luminosity - LHC and beyond
or
How to constrain electric conductivity

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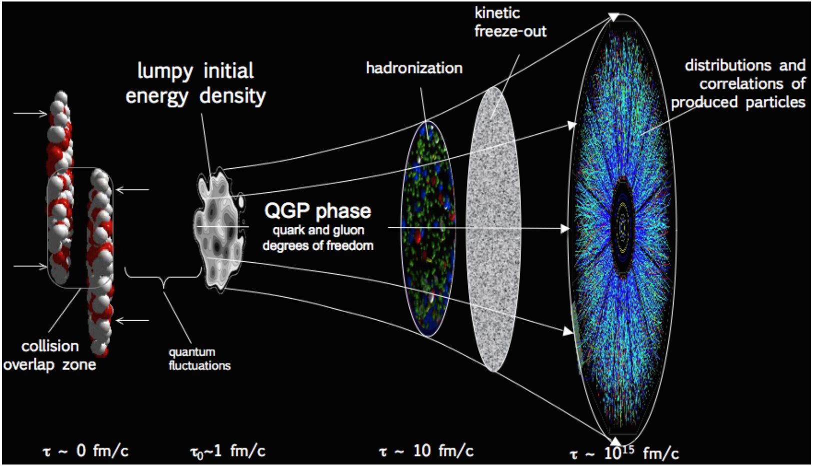
Heavy ions at the HL-LHC

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/
- J. M. Jowett, M. Schaumann and R. Versteegen, *Heavy-Ion Operation of HL-LHC*: https://cds.cern.ch/record/1977371
- 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).

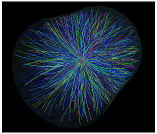
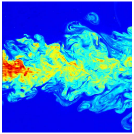
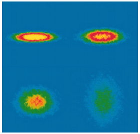
Little bangs in the laboratory



A great challenge

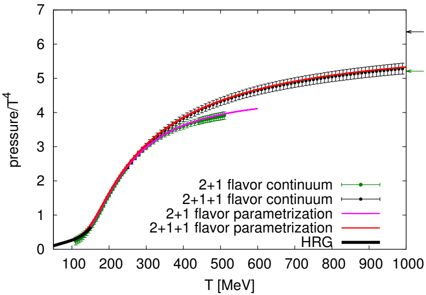
- quantum fields at finite energy density and temperature
- fundamental gauge theory: QCD
- strongly interacting
- non-equilibrium dynamics
- experimentally driven field of research
- big motivation for theory development

Fluid dynamics

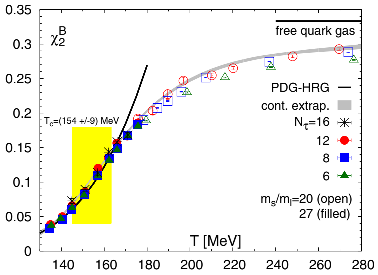
    

- long distances, long times or strong enough interactions
- matter or quantum fields form a fluid!
- needs **macroscopic** fluid properties
  - thermodynamic equation of state $p(T, \mu)$
  - shear viscosity $\eta(T, \mu)$
  - bulk viscosity $\zeta(T, \mu)$
  - heat conductivity $\kappa(T, \mu)$
  - electric conductivity $\sigma(T, \mu)$
  - relaxation times, ...
- *ab initio* calculation of fluid properties difficult but fixed by **microscopic** properties in $\mathscr{L}_{\mathrm{QCD}}$

Thermodynamics of QCD



[Borsányi *et al.* (2016)], similar Bazavov *et al.* (2014)



[Bazavov *et al.* (2017), similar Bellwied *et al.* (2015)]

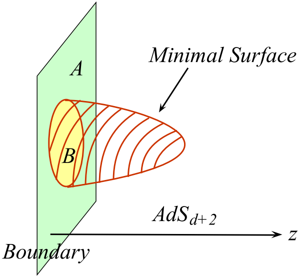
- thermodynamic equation of state $p(T)$ rather well understood now
- also moments of conserved charges like charge susceptibility

$$\chi_2^{\mathrm{Q}} = \frac{\langle Q^2 \rangle}{VT^3}$$

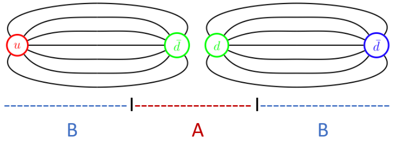
  and higher orders understood
- progress in computing power

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)]

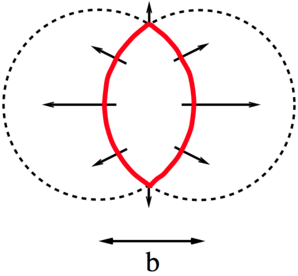


[Ryu, Takayanagi (2006)]



[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

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

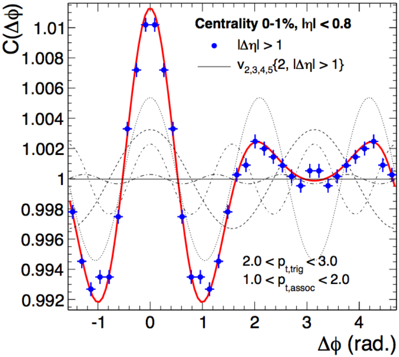
- symmetry $\phi \to \phi + \pi$ implies $v_1 = v_3 = v_5 = \ldots = 0$.

Two-particle correlation function

- normalized two-particle correlation function

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

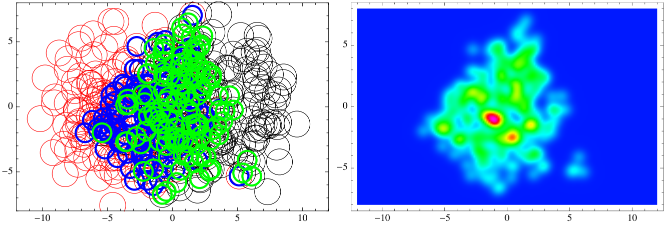
- surprisingly v_2, v_3, v_4, v_5 and v_6 are all non-zero!



[ALICE 2011, similar results from CMS, ATLAS, Phenix, Star]

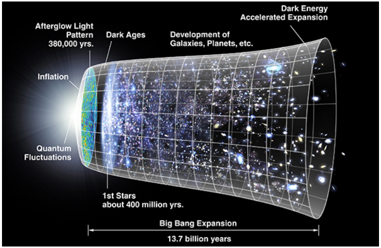
Event-by-event fluctuations

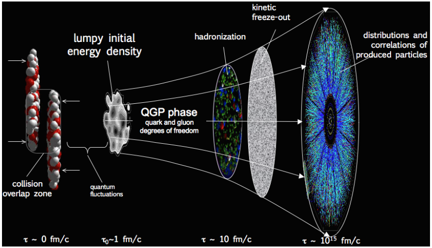
- deviations from symmetric initial energy density distribution from event-by-event fluctuations
- one example is Glauber model



- also initial electric charge distribution is fluctuating!
- can we understand charge transport?
- need to solve also (in medium) Maxwell equations

Big bang – little bang analogy



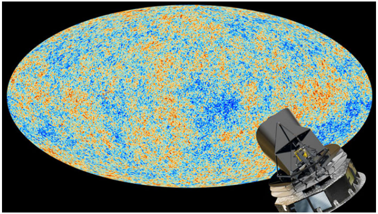


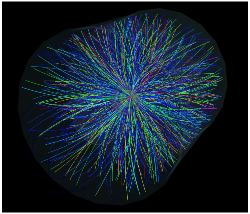
- cosmol. scale: MPc$= 3.1 \times 10^{22}$ m
- Gravity + QED + Dark sector
- one big event

- nuclear scale: fm$= 10^{-15}$ m
- QCD +QED
- 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**

$$\mathscr{L}_{\text{QCD}} \quad \rightarrow \quad \text{fluid properties}$$

- **late time cosmology**

$$\text{fluid properties} \quad \rightarrow \quad \mathscr{L}_{\text{dark matter}}$$

- until direct detection of dark matter it can only be observed via gravity

$$G^{\mu\nu} = 8\pi G_{\text{N}}\, T^{\mu\nu}$$

  so all we can access is

$$T^{\mu\nu}_{\text{dark matter}}$$

- strong motivation to study heavy ion collisions and cosmology together!

Theory development

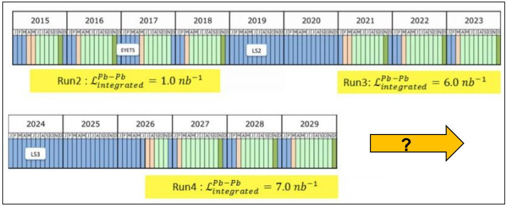
- many interesting experimental results available or in reach
- precise studies need interplay of theory and experiment
- **more dedicated theory development needed**
- **we need to develop and maintain a standard model**
- heavy ion collisions and QCD dynamics can be understood much better !

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)

$\sigma_{hadr,PbPb}$ = 8 barn !



HL-LHC for heavy ions begins in Run 3 !

Foreseen detector upgrades

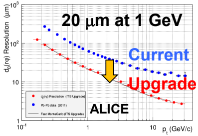
[J.-F. Grosse-Oetringhaus, CERN, 30.10.2017]

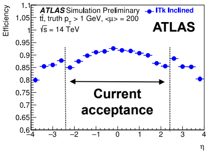
CERN

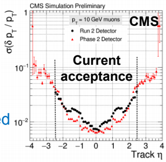
Detector Upgrades

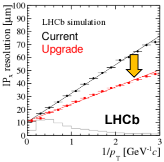
most relevant to heavy-ion physics

- **ALICE** (LS2)
  - New inner tracker: precision and efficiency at low p_T
  - New pixel forward muon tracker: precise tracking and vertexing for μ
  - TPC upgrade + readout + online data reduction x100 faster readout (continuous)
- **ATLAS** (LS2/LS3)
  - Fast tracking trigger (LS2): high-multiplicity tracking
  - Calorimeter and muon upgrades (LS2): electron, γ, muon triggers
  - ZDC replacement planned (LS2): radiation hardness, granularity
  - Completely new tracker (LS3): tracking and b-tag up to η=4
- **CMS** (mainly LS3)
  - Extension of forward muon system (LS2): muon acceptance
  - Completely new tracker (LS3): tracking and b-tag up to η=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



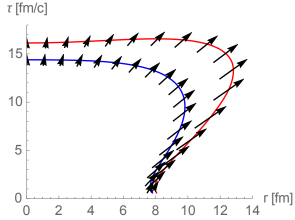






Higher energies

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



Quantity	Pb–Pb 2.76 TeV	Pb–Pb 5.5 TeV	Pb–Pb 39 TeV
$\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ at $\eta = 0$	1600	2000	3600
Total N_{ch}	17000	23000	50000
$\mathrm{d}E_{\mathrm{T}}/\mathrm{d}\eta$ at $\eta = 0$	1.8–2.0 TeV	2.3–2.6 TeV	5.2–5.8 TeV
Homogeneity volume	5000 fm^3	6200 fm^3	11000 fm^3
Decoupling time	10 fm/c	11 fm/c	13 fm/c
ε at $\tau = 1$ fm/c	12–13 GeV/fm^3	16–17 GeV/fm^3	35–40 GeV/fm^3

Larger collision energy

- higher initial energy density and temperature
- higher multiplicity N_{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 $\approx \frac{1}{20 \text{ fm}}$?
- probe macroscopic properties of QCD fluid: very soft pions, kaons, protons, di-leptons
  $\rightarrow$ dynamics of chiral symmetry restoration
  $\rightarrow$ pion condensates / disoriented chiral condensates ?
- understand thermalization and dissipation in detail
  $\rightarrow$ spectrum also at $p_T \ll T_{\text{kinetic freeze-out}} \approx 120$ MeV
- low momentum di-leptons
  $\rightarrow$ excellent understanding of charmonia and bottomonia
  $\rightarrow$ access to transport peak and electric conductivity

Electric current

- quarks are charged and carry electric charge
- four-current composed of net charge density and current density

$$J^\mu(t, \mathbf{x}) = (\rho(t, \mathbf{x}),\ \mathbf{j}(t, \mathbf{x}))$$

- source for electro-magnetic field A_μ in Maxwell equations
- expectation value and fluctuation part

$$J^\mu(x) = \langle J^\mu(x) \rangle + \delta J^\mu(x)$$

- expectation value from net charge of quark-gluon plasma
- initial state, thermal and quantum fluctuations

Correlation and response functions in thermal equilibrium

- **statistical correlation function** $\Delta_S^{\mu\nu}(\omega, \mathbf{k})$ defined by

$$\frac{1}{2}\langle \delta J^\mu(t_1, \mathbf{x}_1)\delta J^\nu(t_2, \mathbf{x}_2) + \delta J^\nu(t_2, \mathbf{x}_2)\delta J^\mu(t_1, \mathbf{x}_1)\rangle$$
$$= \int \frac{d\omega d^3k}{(2\pi)^4} e^{-i\omega(t_1-t_2)+i\mathbf{k}(\mathbf{x}_1-\mathbf{x}_2)} \Delta_S^{\mu\nu}(\omega, \mathbf{k})$$

- quantifies amount of thermal and quantum fluctuations

- **spectral function** $\Delta_\rho^{\mu\nu}(\omega, \mathbf{k})$ defined by

$$\langle \delta J^\mu(t_1, \mathbf{x}_1)\delta J^\nu(t_2, \mathbf{x}_2) - \delta J^\nu(t_2, \mathbf{x}_2)\delta J^\mu(t_1, \mathbf{x}_1)\rangle$$
$$= \int \frac{d\omega d^3k}{(2\pi)^4} e^{-i\omega(t_1-t_2)+i\mathbf{k}(\mathbf{x}_1-\mathbf{x}_2)} \Delta_\rho^{\mu\nu}(\omega, \mathbf{k})$$

- response of current to change in electro-magnetic field $A_\mu(t_2, \mathbf{x}_2)$

- both functions depend also on temperature T
- definitions extend beyond equilibrium

Charge conservation

- charge conservation law in local form

$$\partial_\mu J^\mu(t, \mathbf{x}) = \frac{\partial}{\partial t}\rho(t, \mathbf{x}) + \nabla \cdot \mathbf{j}(t, \mathbf{x}) = 0$$

- implies for correlation functions $k_\mu \Delta^{\mu\nu} = 0$ and in equilibrium

$$-\omega^2 \Delta^{00}(\omega, \mathbf{k}) + \mathbf{k}^2 \Delta^{11}(\omega, \mathbf{k}) = 0$$

- implies in particular

$$\Delta^{00}(\omega, \mathbf{k} = 0) = 0 \qquad (\text{for} \quad \omega \neq 0)$$

The fluctuation-dissipation relation

- close to thermal equilibrium one has **fluctuation-dissipation relation**

$$\Delta_S^{\mu\nu}(\omega, \mathbf{k}) = \left[\frac{1}{2} + \frac{1}{e^{\omega/T} - 1}\right] \Delta_\rho^{\mu\nu}(\omega, \mathbf{k})$$

- statistical correlation function $\Delta_S^{\mu\nu}(\omega, \mathbf{k}) \rightarrow$ fluctuation
- spectral function $\Delta_\rho^{\mu\nu}(\omega, \mathbf{k}) \rightarrow$ dissipation
- contains Bose-Einstein distribution factor

$$\left[\frac{1}{2} + \frac{1}{e^{\omega/T} - 1}\right] \rightarrow \frac{T}{\omega} \quad (T \gg w)$$

- would be very interesting to test! (test of equilibration)

Photon and di-lepton rates

- photon rate

$$\omega \frac{dR}{d^3k} = \frac{1}{16\pi^3} g_{\mu\nu} \Delta_{\rho}^{\mu\nu}(\omega, \mathbf{k})$$

- thermal di-lepton rate (leading order)

$$\begin{aligned}\frac{dW}{d\omega d^3k} &= \frac{\alpha}{24\pi^4(-\omega^2 + \mathbf{k}^2)} g_{\mu\nu} \Delta_{\mathsf{S}}^{\mu\nu}(\omega, \mathbf{k}) \\ &\quad - \text{ zero temperature expression} \\ &= \frac{\alpha}{24\pi^4(-\omega^2 + \mathbf{k}^2)(e^{\omega/T} - 1)} g_{\mu\nu} \Delta_{\rho}^{\mu\nu}(\omega, \mathbf{k})\end{aligned}$$

- allows to probe statistical correlation function
- related to spectral density through fluctuation-dissipation relation
- sensitive to transport peak (conductivity) for $\omega \ll T$, $|\mathbf{k}| \approx 0$

Electric conductivity

- electric conductivity from spatial components of spectral density

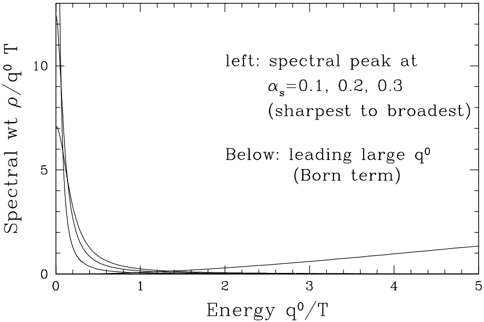
$$\sigma = \frac{1}{6} \lim_{\omega/T \to 0} \frac{\sum_{i=1}^{3} \Delta_{\rho}^{ii}(\omega, \mathbf{k} = 0)}{\omega}$$

- "transport peak" in spectral density for $\omega \ll T$ and $|\mathbf{k}| \approx 0$
- could be constrained through charge transport in electric field

$$\mathbf{j}(t, \mathbf{x}) = \sigma \, \mathbf{E}(t, \mathbf{x})$$

- leads eventually to dissipation of electric fields

Transport peak in spectral function



[Moore & Robert (2006)]

- "spectral weight" $\rho = g_{\mu\nu}\Delta_{\rho}^{\mu\nu}(\omega, \mathbf{k}=0) = \sum_{i=1}^{3} \Delta_{\rho}^{ii}(\omega, \mathbf{k}=0)$
- directly accessible through di-lepton rate
- transport peak at $\omega/T \to 0$ determined by electric conductivity σ

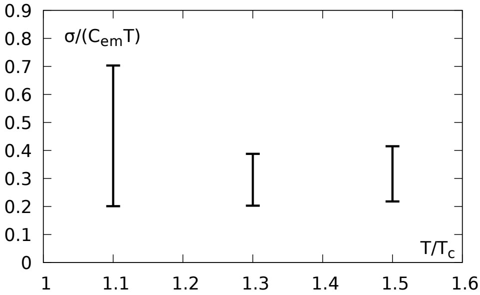
Electric conductivity, theory expectations

- perturbation theory [Arnold, Moore, Yaffe (2000)]

$$\sigma \sim \frac{T}{e^2 \ln e^{-1}}$$

- lattice QCD calculation (with $C_{\text{em}} = e^2 \sum_f Q_f^2$)

$$\sigma \sim T$$



[Ding, Kaczmarek & Meyer (2016)]

Conclusions

- collective physics at low p_T is very interesting
- could allow to test fluctuation-dissipation relation and access electric conductivity through di-leptons
- new fundamental transport property of QCD!
- understanding also charge transport
  $\rightarrow$ test of fluctuation-dissipation relation
- QCD fluid can be understood in much more detail with combined effort of theory and experiment!