Report on European Particle Physics Strategy input from Heavy Ion physics

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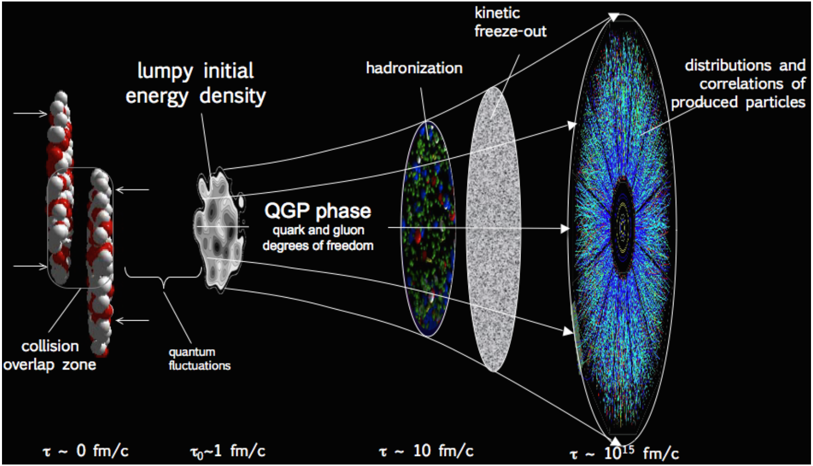
Discussion process so far

- *Future Hadron Colliders at the Energy Frontier*, workshop by KET, KAT and KHuK, 14./15. Dec 2017 at DESY
- *Strategieworkshop Teilchenphysik*, workshop by KET, KAT and KHuK, 3./4. May 2018 in Bonn
- *Town meeting Relativistic Heavy Ion Collisions*, 24. Oct 2018, CERN
- *Heavy ions at the High Luminosity - LHC*, CERN Yellow report & ongoing workshop on *The physics of HL-LHC, and perspectives on HE-LHC*

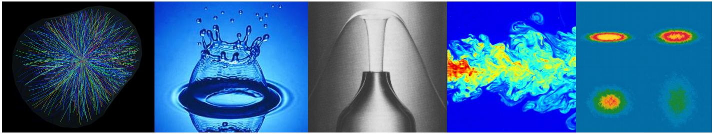
Little bangs in the laboratory



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 $\mathscr{L}_{\text{QCD}}$

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^μ, $\Delta^{\mu\nu} = g^{\mu\nu} + u^\mu u^\nu$
- 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** ϵ

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

- equation for **fluid velocity** u^μ

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

- 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** $\pi^{\mu\nu}$

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

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

- equation for **bulk viscous pressure** π_{bulk}

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

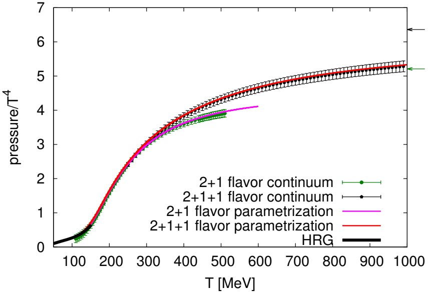
  with **bulk viscosity** $\zeta(T, \mu)$

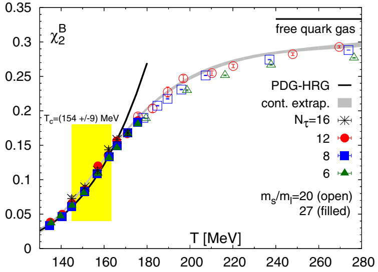
- equation for **baryon diffusion current** ν^μ

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

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

Thermodynamics of QCD





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

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

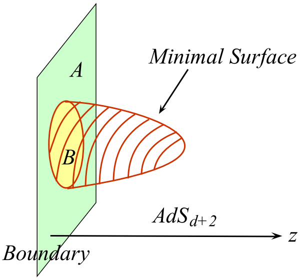
- thermodynamic equation of state $p(T)$ rather well understood now
- also moments of conserved charges like

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

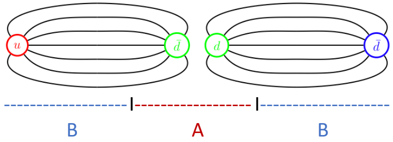
  and higher order understood
- progress in computing power

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)]

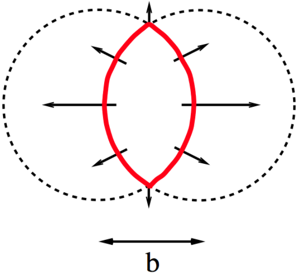


[Ryu, Takayanagi (2006)]



[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

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

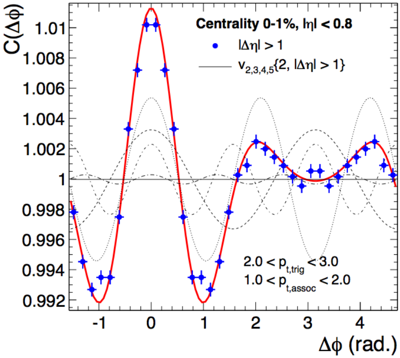
- symmetry $\phi \to \phi + \pi$ implies $v_1 = v_3 = v_5 = \ldots = 0.$

Two-particle correlation function

- normalized two-particle correlation function

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

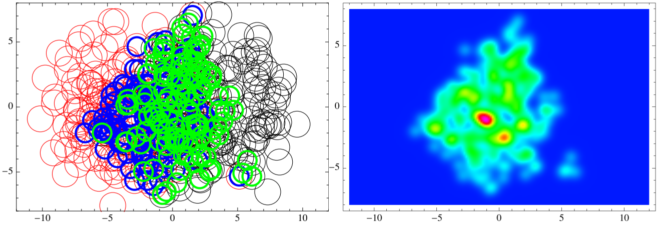
- surprisingly v_2, v_3, v_4, v_5 and v_6 are all non-zero!



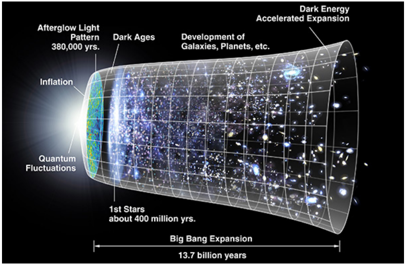
[ALICE 2011, similar results from CMS, ATLAS, Phenix, Star]

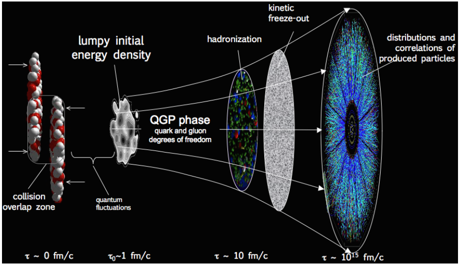
Event-by-event fluctuations

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



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
- very many events

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

The dark matter fluid

- **high energy nuclear collisions**

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

- **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

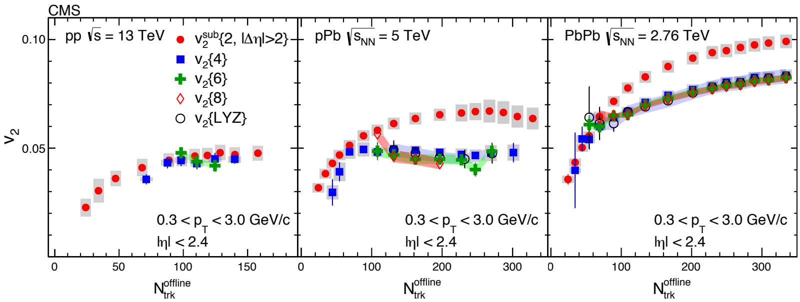
$$G^{\mu\nu} = 8\pi G_{\mathsf{N}}\, T^{\mu\nu}$$

  so all we can access is

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

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

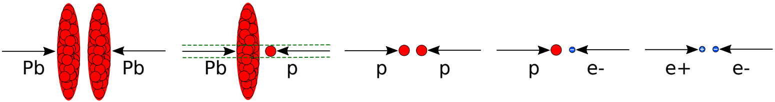
Collective behavior in large and small systems



- flow coefficients from higher order cumulants $v_2\{n\}$ agree:
  $\rightarrow$ collective behavior
- elliptic flow signals also in **pPb** and **pp** !
- can fluid approximation work for pp collisions?

Questions and puzzles

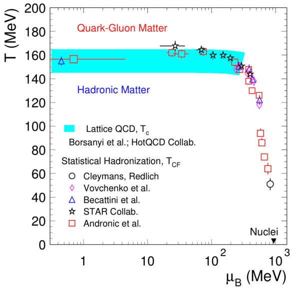
- how universal are collective flow and fluid dynamics?
  - as a limit of kinetic theory / perturbation theory / multi-parton interactions
  - non-perturbative understanding / entanglement
- what determines density distribution of a proton?
  - constituent quarks or interacting gluon cloud?
  - generalized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

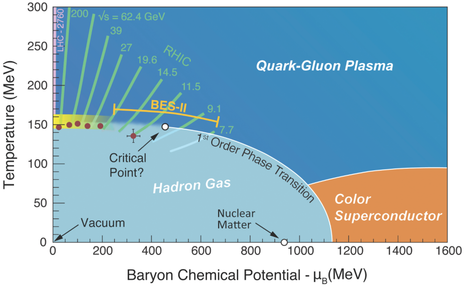


- role of electromagnetic fields and vorticity for fluid dynamics
- role of quantum anomalies (e. g. chiral magnetic effect)

Chemical freeze-out

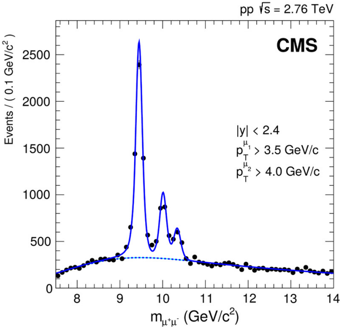
[Andronic, Braun-Munzinger, Redlich, Stachel (2017)]

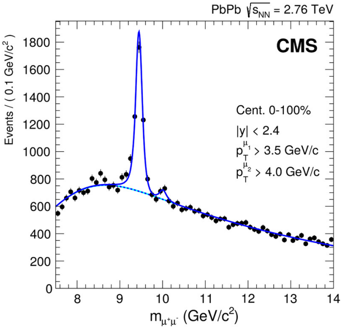




- chemical freeze-out close to chiral crossover transition for large $\sqrt{s}$
- chiral transition should be visible in higher moments $\langle (N_B - N_{\bar{B}})^n \rangle$
- traces of the evolving chiral condensate / pion condensate ?
- more insights at large μ_B expected from FAIR

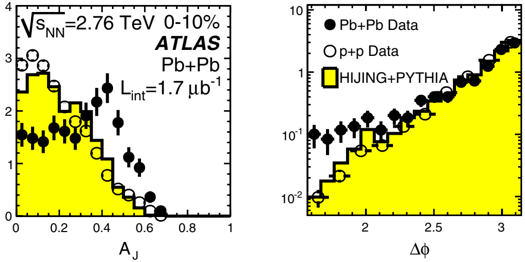
Quarkonium and how it gets modified





- all Υ 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



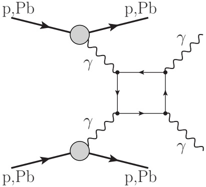
- asymmetry between reconstructed jet energies

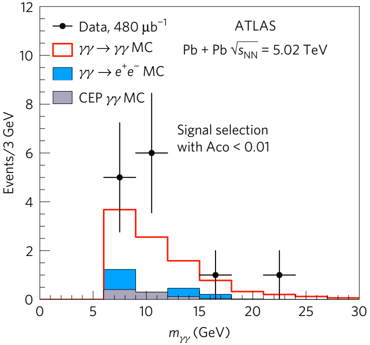
$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \qquad \Delta\phi > \pi/2$$

- partons/jets loose 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 $\gamma\gamma \to \gamma\gamma$ 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 !

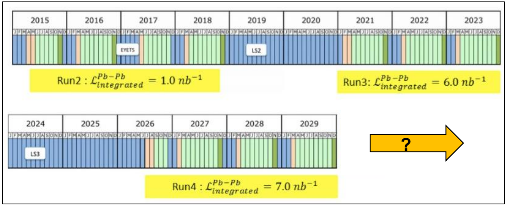
Plans for heavy ions at runs 2-4 at the LHC

[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)

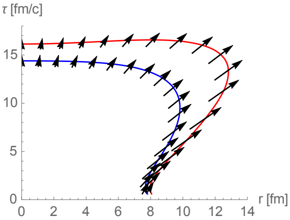
$\sigma_{hadr,PbPb}$ = 8 barn !

HL-LHC for heavy ions begins in Run 3 !



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 $\mathrm{GeV/fm}^3$	16–17 $\mathrm{GeV/fm}^3$	35–40 $\mathrm{GeV/fm}^3$

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 $\approx \frac{1}{20 \text{ fm}}$?
- low momentum di-leptons
  $\rightarrow$ excellent understanding of charmonia and bottomonia (P-wave)
- 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

Abschlusserklärung:

- "...Schwerionen-Kollisionen bei substanziell erhöhten Luminositäten und Energien eröffnen exzellente neue Möglichkeiten zur Untersuchung stark wechselwirkender Materie bei hohen Temperaturen."
- " ... Zusammenhang zwischen den makroskopischen Fluid-Eigenschaften des Quark-Gluon Plasmas und der mikroskopischen QCD Physik"
- "... insbesondere ... identifizierte Teilchen mit sehr kleinen Transversalimpulsen (< 20 MeV/c) von großem Interesse."
- "... Entwicklung eines neuartigen Detektors, basierend auf modernster strahlenharter Siliziumtechnologie, in der nächsten Zeit realisierbar."
- "... Experiment der nächsten Generation ... am HL-LHC ab 2030 beginnen ... finden an zukünftigen Beschleunigern mit höheren Energien eine natürliche Fortsetzung."
- "... Erforschung des QCD Phasendiagramms ... zusätzlich ... Variation der Kollisionsenergie hin zu niedrigeren Temperaturen und höheren Dichten ... Compressed-Baryonic-Matter-Experiment an FAIR von besonderem Interesse."

Town meeting "Relativistic Heavy Ion Collisions" CERN, Oct 2018

Conclusions:

- "The top priority for future quark matter research in Europe is the full exploitation of the physics potential of nucleus-nucleus and proton-nucleus collisions at the LHC."
- "At lower center of mass energies where the highest baryon densities are reached, advances in accelerator and detector technologies provide opportunities for a new generation of precision measurements that address central questions about the QCD phase diagram."
- "The complementarity of LHC and RHIC is an essential resource in efforts to quantify properties of the Quark-Gluon Plasma."
- "Dedicated investments in theoretical research are needed to fully exploit the opportunities arising from the upcoming precision era of nuclear research at collider and fixed target energies."

CERN yellow report and workshop "Physics of the HL-LHC"

- "Characterizing the macroscopic long-wavelength properties of the QGP with unprecedented precision."
- "Accessing the microscopic parton dynamics underlying QGP properties."
- "Developing a unified picture of QCD particle production from small (pp) to larger (pA and AA) systems."
- "Probing nuclear parton densities in a broad (x, Q^2) range, searching for the possible onset of parton saturation."