Heavy ion physics 1 & 2

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# Content

- 1. Motivation and introduction
- 2. Basic quantum chromodynamics
- 3. Particle production in heavy ion collisions
- 4. Thermodynamics and fluid dynamics
- 5. Fluid dynamics of the fireball for more and more realistic initial conditions
- 6. Initial state fluctuations and their fluid dynamic propagation
- 7. Jet quenching
- 8. Quarkonia in hot matter
- 9. Conclusions

1. Motivation and introduction

# Why heavy ion collisions?

- What happens with QCD at large temperature? Is there a phase transition at the Hagedorn temperature?
- Quantum field theory should be understood not only for few particles or at the conventional vacuum but also at non-zero temperature and density.
- Important also for cosmology and condensed matter physics.
- Heavy ion collisions allow to study one of our fundamental quantum field theories (namely QCD) at non-zero temperature and density.
- Quark gluon plasma has filled the universe from about  $10^{-12}$  s to  $10^{-6}$  s after the big bang. Heavy ion collisions allow to learn something about this state from laboratory experiments.
- Heavy ion physics is an active field of research. Ongoing large experimental programs at the LHC (CERN) by the collaborations ALICE, ATLAS, CMS, LHCb and at RHIC (BNL) by the collaborations Phenix and STAR.

# Heavy Ion Collisions



#### Evolution in time

- Non-equilibrium evolution at early times
  - initial state at from QCD? Color Glass Condensate? ...
  - thermalization via strong interactions, plasma instabilities, particle production, ...
- Local thermal and chemical equilibrium
  - strong interactions lead to short thermalization times
  - evolution from relativistic fluid dynamics
  - expansion, dilution, cool-down
- Chemical freeze-out
  - for small temperatures one has mesons and baryons
  - inelastic collision rates become small
  - particle species do not change any more
- Thermal freeze-out
  - elastic collision rates become small
  - particles stop interacting
  - particle momenta do not change any more

2. Basic quantum chromodynamics (QCD)

## $Microscopic \ description$

Lagrangian

$$\mathscr{L} = -\frac{1}{2} \operatorname{tr} \mathbf{F}_{\mu\nu} \mathbf{F}^{\mu\nu} - \sum_{f} \bar{\psi}_{f} \left( i \gamma^{\mu} \mathbf{D}_{\mu} - m_{f} \right) \psi_{f}$$

with

$$\mathbf{F}_{\mu\nu} = \partial_{\mu} \mathbf{A}_{\nu} - \partial_{\nu} \mathbf{A}_{\mu} - ig[\mathbf{A}_{\mu}, \mathbf{A}_{\nu}], \qquad \mathbf{D}_{\mu} = \partial_{\mu} - ig\mathbf{A}_{\mu}$$

Particle content

- $N_c^2 1 = 8$  real massless vector bosons: gluons
- $N_c \times N_f$  massive Dirac fermions: quarks

Quark masses

Up	2.3 MeV	Charm	1275 MeV	Тор	173 GeV
Down	4.8 MeV	Strange	95 MeV	Bottom	4180 MeV

# Asymptotic freedom



- Coupling constant small at high momentum transfer / energy scale
- High-temperature QCD should be weakly coupled
- Low-temperature QCD should be strongly coupled

### Confinement - deconfinement



- For low temperature / density: quarks and gluons confined to hadrons
- For high temperature / density: deconfined quarks and gluons
- In between no sharp phase transition but continuous crossover

3. Particle production in heavy ion collisions

### Collision energies

- Large Hadron Collider (LHC), run 1
  - total collision energy for Pb-Pb

$$\sqrt{s} = 2 \times 574 \, \mathrm{TeV}$$

- ${}^{208}$ Pb has 82 + 126 = 208 nucleons
- collision energy per nucleon

$$\sqrt{s_{\mathsf{NN}}} = \frac{574}{208} \, \mathsf{TeV} = 2.76 \, \mathsf{TeV}$$

- also proton-ion collisions (pA) at  $\sqrt{s_{\rm NN}} = 5.02\,{\rm GeV}$
- Lower energy experiments
  - Alternating Gradient Synchrotron (AGS) at BNL (since mid 1980's)

 $\sqrt{s_{\rm NN}} pprox 2 - 5 \,{\rm GeV}$ 

• CERN SPS fixed target experiments (since 1994)

 $\sqrt{s_{\mathsf{NN}}} \leq 17\,\mathsf{GeV}$ 

• Relativistic Heavy Ion Collider (RHIC) at BNL (since 2000)

 $\sqrt{s_{\rm NN}} \le 200 \, {\rm GeV}$ 

# Multiplicity

Number of charged particles found in the detector



- as function of pseudo-rapidity  $\eta = -\ln(\tan(\theta/2))$
- $\bullet$  integration gives  $N_{\rm ch} = 5060 \pm 250$  at upper RHIC energy
- not all particles are charged, about  $1.6 \times 5060 \approx 8000$  hadrons in total
- $N_{\rm ch}$  grows with collision energy
- estimate for LHC:  $N_{\rm ch} = 25\,000$  or about  $40\,000$  hadrons in total

# Identified particle multiplicities



[Andronic, Braun-Munzinger, Redlich, Stachel (2012/2013)]

Multiplicities of identified particles well described by statistical model:

- non-interacting hadron resonance gas in thermal and chemical equilibrium.
- includes all hadronic resonances known to the particle data group.
- fit parameters are temperature T, volume V and chemical potentials for baryon number  $\mu_b$ , isospin, strangness and charm.

# $Chemical\ freeze-out\ interpretation$

- Why does statistical model work that well?
- Hadronization is governed by non-perturbative QCD processes. Not completely understood yet.
- Interpretation in terms of chemical freeze-out:
  - Close-to-equilibrium evolution with expansion and cool-down
  - Number changing processes are first fast and keep up equilibrium
  - At low temperature they become too slow to keep up with the expansion
  - Particle numbers get frozen in
- Interpretation seems reasonable for heavy ion collisions.
- Puzzle: Statistical model works also for electron-positron collisions with similar temperatures.

### Statistical model fits and collision energy

Statistical model fits have been made at different collision energies



[Andronic, Braun-Munzinger, Stachel (2009)]

# A phase diagram from chemical freeze-out?

- The fit parameters  $(T,\mu)$  from different collision energies lead to a suggestive diagram.
- But what is the physical significance?



[Andronic, Braun-Munzinger, Stachel (2009), LQCD from Fodor, Katz (2004)]

4. Thermodynamics and fluid dynamics (from a theoretical perspective)

### QCD thermodynamics

• Stefan-Boltzmann law: pressure of  $N_B$  real massless bosons and  $N_F$  real massless fermions (in units with  $\hbar = k_B = c = 1$ )

$$p(T) = \frac{\pi^2}{90} \left( N_B + \frac{7}{8} N_F \right) T^4$$

• For QCD at high temperatures  $N_c = 3$  colors,  $N_f = 3$  quark flavors

$$N_B = 2 \times (N_c^2 - 1) = 16, \qquad N_F = 4 \times N_c \times N_f = 36$$

- Corrections to this arise from quark masses and interactions.
- For smaller temperatures there are less effective degrees of freedom. For example for  $M_{\pi} < T < M_{\rho}$  one has approximately

$$N_B = 3, \qquad N_F = 0$$

- At low temperatures p(T) can be calculated from Hadron resonance gas.
- For transition region one needs Lattice QCD.

Thermodynamic equation of state from Lattice QCD



[Borsanyi, et al. (2010)]

- Results are for vanishing baryon, strangeness, electric charge etc. chemical potentials µ<sub>b</sub> = µ<sub>S</sub> = ... = 0.
- This regime is most relevant for heavy ion collisions at high energy.
- Can be extended to  $p(T, \mu_b, \mu_S, ...)$  by Taylor expansion technique.
- All thermodynamic information can be derived from  $p(T, \mu_b, \mu_S, \ldots)$ .

# Fluid dynamics



- long distances, long times, strong interactions
- quantum fields form a fluid!
- works well for heavy ion collisions
- needs macroscopic material properties
  - equation of state p(T)
  - shear viscosity  $\eta(T)$
  - bulk viscosity  $\zeta(T)$
  - heat conductivity  $\kappa(T)$
  - relaxation times  $\tau_{\rm shear}(T)$ ,  $\tau_{\rm bulk}(T)$  etc.
- old dream of condensed matter theorists: determine them!

# Ideal fluid dynamics

• For a fluid in *global* thermal equilibrium the energy-momentum tensor can be written as

$$T^{\mu\nu} = \epsilon u^{\mu}u^{\nu} + p\left(g^{\mu\nu} + u^{\mu}u^{\nu}\right)$$

with metric  $g_{\mu\nu} = \text{diag}(-1, 1, 1, 1)$  and fluid velocity  $u^{\mu}$ .

 $\bullet\,$  Pressure p is related to energy density  $\epsilon$  by thermodynamic equation of state

$$p = p(\epsilon)$$

• The ideal fluid approximation assumes <code>local</code> thermal equilibrium, i.e.  $T^{\mu\nu}$  is of the form above with

$$\epsilon = \epsilon(x), \qquad u^{\mu} = u^{\mu}(x).$$

• From conservation law of energy-momentum  $\nabla_{\mu}T^{\mu\nu} = 0$ , one obtains evolution equations for  $\epsilon(x)$  and  $u^{\mu}(x)$  in ideal fluid dynamics

$$u^{\mu}\partial_{\mu}\epsilon + (\epsilon + p)\nabla_{\mu}u^{\mu} = 0,$$
  
$$(\epsilon + p)u^{\mu}\nabla_{\mu}u^{\nu} + (g^{\nu\mu} + u^{\nu}u^{\mu})\partial_{\mu}p = 0.$$

#### Viscous relativistic fluid dynamics

• Write now more general (with  $\Delta^{\mu\nu}=g^{\mu\nu}+u^{\mu}u^{\nu})$ 

$$T^{\mu\nu} = \epsilon \, u^{\mu} u^{\nu} + \left( p + \pi_{\mathsf{bulk}} \right) \Delta^{\mu\nu} + \pi^{\mu\nu}$$

where  $\pi^{\mu\nu}$  is transverse  $u_{\mu}\pi^{\mu\nu}=0$  and traceless  $\pi^{\mu}_{\ \mu}=0$ .

- The bulk viscous pressure  $\pi_{\rm bulk}$  and shear stress  $\pi^{\mu\nu}$  parametrize deviations from ideal fluid dynamics
- Viscous fluid dynamics can be organized as a derivative expansion

$$\pi_{\text{bulk}} = -\zeta \nabla_{\mu} u^{\mu} + \dots,$$
  
$$\pi^{\mu\nu} = -2\eta \left( \frac{1}{2} \Delta^{\mu\alpha} \Delta^{\nu\beta} + \frac{1}{2} \Delta^{\mu\beta} \Delta^{\nu\alpha} - \frac{1}{3} \Delta^{\mu\nu} \Delta^{\alpha\beta} \right) \nabla_{\alpha} u_{\beta} + \dots$$

- First order depends on bulk viscosity  $\zeta = \zeta(\epsilon)$  and shear viscosity  $\eta = \eta(\epsilon)$ .
- At second order relaxation times  $\tau_{\rm shear}(\epsilon)$  and  $\tau_{\rm bulk}(\epsilon)$  as well as other terms.

### Evolution equation for energy density

Evolution equation for energy density becomes for viscous theory

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

• Non-relativistic limit gives for first order approximation

$$\partial_t \epsilon + \vec{v} \cdot \vec{\nabla} \epsilon + (\epsilon + p) \vec{\nabla} \cdot \vec{v} = \zeta \left( \vec{\nabla} \cdot \vec{v} \right)^2 + 2 \eta \, \sigma_{ij} \sigma_{ij}$$

with 
$$\sigma_{ij} = \frac{1}{2}\partial_i v_j + \frac{1}{2}\partial_j v_i - \frac{1}{3}\delta_{ij}(\vec{\nabla}\cdot\vec{v}).$$

- Left hand side describes thermodynamic work by expansion or contraction.
- Right hand side gives dissipation of fluid kinetic energy to thermal energy.
- Thermodynamic relations  $\epsilon + p = sT$  and  $d\epsilon = Tds$  lead to equation for entropy production

$$\partial_t s + \vec{\nabla} \cdot (s\vec{v}\,) = \frac{\zeta}{T} \left(\vec{\nabla} \cdot \vec{v}\right)^2 + \frac{2\eta}{T} \,\sigma_{ij}\sigma_{ij}$$

## $Relativistic\ Navier-Stokes\ equation$

Evolution equation for fluid velocity becomes for viscous theory

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

 Non-relativistic limit gives for first order approximation the non-relativistic Navier-Stokes equation

$$\rho \left[ \partial_t v_j + \vec{v} \cdot \vec{\nabla} v_j \right] + \partial_j p = \partial_j \left( \zeta \vec{\nabla} \cdot \vec{v} \right) + \partial_m \left( 2 \eta \, \sigma_{jm} \right)$$

- Second term on the left hand side describes acceleration by pressure gradients.
- Terms on right hand side describe damping by viscosity.
- In general, equations for  $\epsilon$  and  $u^{\mu}$  get closed by relations for  $\pi_{\text{bulk}}$  and  $\pi^{\mu\nu}$  (so called constitutive relations).

# Transport properties

- Viscosity is due to transport of momentum. For  $\eta/s$  to be large, momentum must be transported efficiently over distances  $s^{-1/3}$  by well defined quasiparticles.
- Theories with small  $\eta/s$  have no well defined quasiparticles.
- Transport properties like shear viscosity, bulk viscosity, heat conductivity, relaxation times, etc. are difficult to determine from quantum field theory.
- Lattice QCD calculations in Euclidean space cannot determine them directly.
- Analytic continuation from Euclidean to Minkowski space is numerically very difficult.
- Concrete expressions can be obtained for very weakly interacting theories from perturbation theory (or mapping to kinetic theory) or for strongly interacting theories with gravity dual.
- For theories that are neither very weakly nor very strongly interacting the determination of transport properties is essentially an open problem.

Shear and bulk viscosity for non-relativistic gas

• Shear viscosity for a simple non-relativistic gas from kinetic theory

 $\eta = \tau_{\rm f} n T$ 

with particle density n, temperature T, mean free time

 $\tau_{\rm f} = \frac{1}{\sigma_{\rm tot}\,\bar{v}\,n}$ 

total elastic cross section  $\sigma_{\rm tot},$  mean velocity  $\bar{v}.$ 

• Using 
$$T=\frac{1}{3}m\bar{v}^2$$
 gives 
$$\eta=\frac{m\,\bar{v}}{3\,\sigma_{\rm tot}}$$

- Viscosity becomes large for small cross-section !
- Bulk viscosity vanishes for simple non-relativistic gas  $\zeta = 0$ .

Shear and bulk viscosity in high temperature QCD

- $\bullet\,$  At very high temperature QCD becomes weakly coupled,  $g\ll 1$
- Shear viscosity at leading logarithmic accuracy [Arnold, Moore, Yaffe (2000)]

$$\eta(T) = k(N_f) \frac{T^3}{g^4 \ln(1/g)}$$

• Bulk viscosity is related via velocity of sound  $c_s$  [Arnold, Dogan, Moore (2006)]

$$\zeta(T) \approx 15\eta(T) \left(\frac{1}{3} - c_s^2(T)\right)^2$$

For very high temperature  $c_s^2 \to 1/3$  and  $\zeta \to 0.$ 

### Shear and bulk viscosity in AdS/CFT

 For many strongly interacting (conformal) theories with gravitational dual one has [Policastro, Son, Starinets (2001)]

$$\eta(T) = s(T)\frac{1}{4\pi}$$

• This was conjectured to be a universal lower bound [Kovtun, Son, Starinets (2005)]

$$\frac{\eta}{s} \ge \frac{\hbar}{4\pi k_B}$$

but theoretical counterexamples have been found. Experimentally, no system seems to violate the bound so far.

• For some theories with deviations from conformal symmetry it was found [Buchel (2005)]

$$\zeta(T) = 2\eta(T) \left(\frac{1}{3} - c_s^2(T)\right)$$

but does not seem to be a universal relation.

5. Fluid dynamics of the fireball for more and more realistic initial conditions

# Initial conditions

- Solution of fluid dynamic equations depends on initial conditions at early time.
- Solution is simpler when initial conditions are simpler / more symmetric.
- In the context of heavy ion collisions, initial conditions are not completely known but some of their features are.
- Discuss in the following first particularly symmetric and then more and more realistic initial conditions and the corresponding solution of fluid dynamics.

### Bjorken boost invariance



How does the fluid velocity look like?

- Bjorkens guess:  $v_z(t, x, y, z) = z/t$
- leads to an invariance under Lorentz-boosts in the z-direction
- use coordinates  $\tau=\sqrt{t^2-z^2}~x,~y,~\eta={\rm arctanh}(z/t)$
- fluid velocity  $u^{\mu} = (u^{\tau}, u^x, u^y, 0)$
- $\bullet$  thermodynamic scalars like energy density  $\epsilon = \epsilon(\tau, x, y)$
- remaining problem is 2+1 dimensional
- Bjorken boost symmetry is an idealization but it is reasonably accurate close to mid-rapidity  $\eta\approx 0.$

### The Bjorken model

[coordinates:  $\tau = \sqrt{t^2 - z^2}$ , x, y,  $\eta = \operatorname{arctanh}(z/t)$ ]

• Consider initial conditions at  $au= au_0$  of the form

$$\epsilon = \epsilon(\tau_0), \qquad u^{\mu} = (1, 0, 0, 0)$$

- Simplified model for inner region at early times after central collision.
- Symmetries
  - Bjorken boost invariance  $\eta \to \eta + \Delta \eta$

 ${\ensuremath{\, \bullet }}$  Translations and rotations in the transverse plane (x,y)

imply

- $u^{\mu} = (1,0,0,0)$  for all times  $\tau$
- $\epsilon=\epsilon(\tau)$  independent of  $x,y,\eta$
- Equation for energy density in first order formalism

$$\partial_{\tau}\epsilon + (\epsilon + p)\frac{1}{\tau} - \left(\frac{4}{3}\eta + \zeta\right)\frac{1}{\tau^2} = 0$$

• Solution depends on equation of state  $p(\epsilon)$  and viscosities  $\eta(\epsilon),\,\zeta(\epsilon)$ 

#### Bjorken solution

 $\bullet~{\rm For}~\epsilon \sim T^4~{\rm one}~{\rm finds}$ 

$$\partial_{\tau}T + \frac{T}{3\tau}\left(1 - \frac{4\eta/3 + \zeta}{sT\tau}\right) = 0$$

• Solution for  $\eta/s = {\rm const}$  and  $\zeta = 0$  is

$$T(\tau) = T(\tau_0) \left(\frac{\tau_0}{\tau}\right)^{1/3} \left[1 + \frac{2}{3\tau_0 T(\tau_0)} \frac{\eta}{s} \left(1 - \left(\frac{\tau_0}{\tau}\right)^{2/3}\right)\right]$$

- $\bullet\,$  For ideal fluid or at late times simply  $T\sim \tau^{-1/3}$
- Small heating effect due to shear viscosity



### Radial expansion



- More realistic initial energy density depends on transverse coordinates
- For central collisions problem becomes 1+1 dimensional, with  $r=\sqrt{x^2+y^2},$   $\epsilon=\epsilon(\tau,r)$
- initial pressure gradient leads to fluid velocity in radial direction: "radial flow"

$$\begin{pmatrix} u^x \\ u^y \end{pmatrix} = \begin{pmatrix} x/r \\ y/r \end{pmatrix} \ u^r(\tau, r)$$

## $Central\ collisions$

System of coupled 1+1 dimensional non-linear partial differential equations for

- $\bullet$  energy density  $\epsilon(\tau,r)$  or temperature  $T(\tau,r)$
- $\bullet$  fluid velocity  $u^r(\tau,r)$
- two independent components of shear stress  $\pi^{\mu\nu}(\tau,r)$

Can be easily solved numerically


#### Kinetic freeze-out

- When temperature and densities drop, collisions become less frequent.
- At some point, hadrons stop interacting, occupation numbers in momentum space do not change any more: Kinetic freeze-out
- Just before freeze-out: local close-to-equilibrium occupation numbers for each fluid element

$$\frac{dN_i}{d^3pd^3x} = f_i(p^{\mu}; T(x), u^{\mu}(x), \pi^{\mu\nu}(x), \pi_{\text{bulk}}(x))$$

 $\bullet\,$  For example, neglecting  $\pi^{\mu\nu}$  and  $\pi_{\rm bulk}$  and assuming Boltzmann statistics

$$f_i = c_i \, e^{\frac{u_\mu(x)p^\mu}{T(x)}} \to c_i \, e^{-\frac{E - \vec{v}(x) \cdot \vec{p}}{T(x)}} \quad (\vec{v}^2 \ll c^2)$$

• Integral over the freeze-out surface or surface of last scattering  $\Sigma_f$  gives particle spectra [Cooper, Frye (1974)]

$$E\frac{dN_i}{d^3p} = -\frac{1}{(2\pi)^3} p_\mu \int_{\Sigma_f} d\Sigma^\mu f_i$$

• Feeze-out surface in principle determined by dynamics of expansion and scattering processes. In practice often assumed to correspond to T = const.

### $Blast-wave\ model$

Not a consistent solution of fluid dynamics but rather a semi-realistic parametrization fluid fields and freeze-out surface.

- assume freeze-out at constant time  $\tau_f$  and freeze-out surface with  $r < r_{\max}$
- $\bullet$  assume also constant temperature T and radial fluid velocity  $v_r$

leads to analytic expression

$$\frac{dN_i}{dyd^2p_T} = \frac{c_i}{4\pi^2} \tau_f r_{\max}^2 \sqrt{p_T^2 + m_i^2} \ K_1 \left(\frac{\sqrt{p_T^2 + m_i^2}}{T\sqrt{1 - v_r^2}}\right) I_0 \left(\frac{p_T v_r}{T\sqrt{1 - v_r^2}}\right)$$

- many variants of this have been studied
- captures some qualitative features of full fluid dynamics solution
- particle spectrum close to exponential
- radial flow leads to a "blue shift" of the particle spectrum
- spectrum steeper for smaller particle mass  $m_i$

#### Charged particle spectra



- For 0-5% most central collisions and small  $p_T$  almost exponential form, determined by freeze-out temperature and radial flow velocity.
- For peripheral collisions similar form as scaled propton-proton reference.

# Mass ordering

Transperse momentum spectra of identified particles for heavy ion and proton-proton collisions





- Spectra for heavier particles fall off more slowly in heavy ion collisions (mass ordering).
- Freeze-out temperature  $T \approx 90$  MeV, radial velocity  $v_r \approx 0.6c$ .
- No systematic mass ordering for pp collisions.

#### 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  $\phi \rightarrow \phi + \pi$  implies  $v_1 = v_3 = v_5 = \ldots = 0$ .

#### $Centrality \ classes$

- Impact parameter cannot be measured directly
- More central collisions have higher multiplicity
- Events are divided into centrality classes



# $Elliptic \ flow$

Elliptic flow coefficient  $v_2$  as a function of  $p_T$  for different centrality classes



#### Elliptic flow at different collision energies

Elliptic flow coefficient  $v_2$  for centrality class 20-30% as a function of  $\sqrt{s_{\sf NN}}$ 



• Elliptic flow in fixed centrality class increases with collision energy.

• At very small energy not enough time to develop flow.

#### Two-particle correlation function

• normalized two-particle correlation function

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

• Surprisingly  $v_2$ ,  $v_3$ ,  $v_4$ ,  $v_5$  and  $v_6$  are all non-zero!



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

# Harmonic flow coefficients

Flow coefficients  $v_2$ ,  $v_3$ ,  $v_4$  and  $v_5$  for charged particles as a function of transverse momentum for different centrality classes.



- Elliptic flow  $v_2$  has strongest centrality dependence.
- Triangular flow  $v_3$  as well as  $v_4$  and  $v_5$  are all non-zero.
- $v_n(p_T)$  at fixed  $p_T$  decreases for increasing n

#### $Event\-by\-event\ fluctuations$

- argument for  $v_3=v_5=0$  is based on event-averaged geometric distribution
- deviations from this can come from event-by-event fluctuations.
- one example is Glauber model



- initial transverse density distribution fluctuates event-by-event and this leads to sizeable  $v_3$  and  $v_5$
- more generally also other initial hydro fields may fluctuate: fluid velocity, shear stress, baryon number density etc

#### Fluid dynamic simulations

- Second order relativistic fluid dynamics is solved numerically for given initial conditions.
- Codes use thermodynamic equation of state from lattice QCD.
- Initial conditions fluctuate from event-to-event and different models are employed and compared.
- $\eta/s$  is varied in order to find experimentally favored value.



[Gale, Jeon, Schenke, Tribedy, Venugopalan (2013)]

#### Collective behavior in small systems



[CMS (2014), similar from ALICE, ATLAS]

- Fluid dynamic behavior was found also in proton-ion collisions.
- Triangular flow very similar for comparable multiplicity.
- Theoretical understanding: Collision geometry smaller but higher initial energy density.

6. Initial state fluctuations and their fluid dynamic propagation

What perturbations are interesting and why?

- Initial fluid perturbations: Event-by-event fluctuations around a background or average of fluid fields at time τ<sub>0</sub>:
  - energy density  $\epsilon$
  - fluid velocity  $u^{\mu}$
  - shear stress  $\pi^{\mu\nu}$
  - more general also: baryon number density n<sub>B</sub>, electric charge density, electromagnetic fields, ...
- governed by universal evolution equations
- can be used to constrain thermodynamic and transport properties
- contain interesting information from early times
- measure for deviations from equilibrium

#### Similarities to cosmic microwave background



- fluctuation spectrum contains info from early times
- many numbers can be measured and compared to theory
- can lead to detailed understanding of evolution and properties
- could trigger precision era in heavy ion physics

# A program to understand fluid perturbations

- Ocharacterize initial perturbations.
- Propagated them through fluid dynamic regime.
- Ø Determine influence on particle spectra and harmonic flow coefficients.
- Take also perturbations from non-hydro sources (jets) into account.

## Fluid dynamic perturbation theory for heavy ions

#### proposed in: [Floerchinger & Wiedemann, PLB 728, 407 (2014)]



- goal: determine transport properties experimentally
- so far: numerical fluid simulations e.g. [Heinz & Snellings (2013)]
- new: solve fluid equations for smooth and symmetric background and order-by-order in perturbations
- less numerical effort more systematic studies
- good convergence properties [Floerchinger et al., PLB 735, 305 (2014)]
- similar technique used in cosmology since many years

# Background-fluctuation splitting

· Background or average over many events is described by smooth fields

```
w_{
m BG} = \langle w 
angle
u^{\mu}_{
m BG} = \langle u^{\mu} 
angle
```

• Fluctuations are added on top

$$w = w_{\rm BG} + \delta w$$
$$u^{\mu} = u^{\mu}_{\rm BG} + \delta u^{\mu}$$

• For background one may assume Bjorken boost and azimuthal rotation invariance

 $w_{\mathrm{BG}} = w_{\mathrm{BG}}( au, r)$  $u_{\mathrm{BG}}^{\mu} = (u_{\mathrm{BG}}^{ au}, u_{\mathrm{BG}}^{r}, 0, 0)$  Characterization of transverse density via Bessel-Fourier expansion

Based on Bessel-Fourier expansion and background density [Floerchinger & Wiedemann 2013, see also Coleman-Smith, Petersen & Wolpert 2012, Floerchinger & Wiedemann 2014]

$$w(r,\phi) = w_{\rm BG}(r) + w_{\rm BG}(r) \sum_{m,l} w_l^{(m)} e^{im\phi} J_m\left(z_l^{(m)}\rho(r)\right)$$

- azimuthal wavenumber m, radial wavenumber l
- $w_l^{(m)}$  dimensionless
- $\bullet\,$  higher m and l correspond to finer spatial resolution
- coefficients  $w_l^{(m)}$  can be related to eccentricieties
- works similar for vectors (velocity) and tensors (shear stress)

#### Transverse density from Glauber model



#### Perturbative response formalism

Write the hydrodynamic fields  $h = (w, u^{\mu}, \pi^{\mu\nu}, \pi_{\mathsf{Bulk}}, \ldots)$ 

• at initial time  $\tau_0$  as

 $h = h_0 + \epsilon h_1$ 

with background  $h_0$ , fluctuation part  $\epsilon h_1$ 

```
• at later time \tau > \tau_0 as
```

$$h = h_0 + \epsilon h_1 + \epsilon^2 h_2 + \epsilon^3 h_3 + \dots$$

Solve for time evolution in this scheme

- $h_0$  is solution of full, non-linear hydro equations in symmetric situation: azimuthal rotation and Bjorken boost invariant
- $h_1$  is solution of linearized hydro equations around  $h_0$ , can be solved mode-by-mode
- $h_2$  can be obtained by from interactions between modes etc.

#### Evolving perturbation modes linearly

- Linearized hydro equations: set of coupled 3 + 1 dimensional, linear, partial differential equations.
- Use Fourier expansion

$$h_j(\tau, r, \phi, \eta) = \sum_m \int \frac{dk_\eta}{2\pi} h_j^{(m)}(\tau, r, k_\eta) e^{i(m\phi + k_\eta \eta)}$$

- Reduces to 1+1 dimensions.
- Can be solved numerically for each initial Bessel-Fourier mode.



- Non-linear terms in the evolution equations lead to mode interactions.
- Quadratic and higher order in initial perturbations.
- Can be determined from iterative solution but has not been fully worked out yet.
- Convergence can be tested with numerical solution of full hydro equations.

#### $Freeze-out\ surface$

- Background and fluctuations are propagated until  $T_{\rm fo}=120\,{\rm MeV}$  is reached.
- Distribution functions are determined and free streaming is assumed for later times [Cooper & Frye].
- Perturbative expansion can be used also at freeze-out. [Floerchinger, Wiedemann 2013]
- Freeze-out surface is azimuthally symmetric as background.
- Generalization to kinetic hadronic scattering and decay phase possible.



#### Particle distribution

for single event

$$\ln\left(\frac{dN^{\text{single event}}}{p_T dp_T d\phi dy}\right) = \underbrace{\ln S_0(p_T)}_{\text{from background}} + \underbrace{\sum_{m,l} w_l^{(m)} e^{im\phi} \theta_l^{(m)}(p_T)}_{\text{from fluctuations}}$$

 $\bullet$  each mode comes with an angle,  $w_l^{(m)} = |w_l^{(m)}| \, e^{i m \psi_l^{(m)}}$ 

- each mode has different  $p_T$ -dependence,  $\theta_l^{(m)}(p_T)$
- quadratic order correction

η

$$\sum_{n_1,m_2,l_1,l_2} w_{l_1}^{(m_1)} w_{l_2}^{(m_2)} e^{i(m_1+m_2)\phi} \kappa_{l_1,l_2}^{(m_1,m_2)}(p_T)$$

non-linearities from hydro evolution and freeze-out

#### Response to density perturbations

#### For a single event

$$V_m^* = v_m e^{-i m \psi_m}$$
  
=  $\sum_l S_{(m)l} w_l^{(m)} + \sum_{\substack{m_1, m_2, \ l_1, l_2}} S_{(m_1, m_2)l_1, l_2} w_{l_1}^{(m_1)} w_{l_2}^{(m_2)} \delta_{m, m_1 + m_2} + \dots$ 

- $S_{(m)l}$  is linear dynamic response function
- $S_{(m_1,m_2)l_1,l_2}$  is quadratic dynamic response function etc.
- Symmetries imply conservation of azimuthal wavenumber
- Response functions depend on thermodynamic and transport properties, in particular viscosity.

#### "Proof of principle" study: One-particle spectrum

Initial conditions from Glauber Monte Carlo Model

 $S(p_T) = dN/(2\pi p_T dp_T d\eta d\phi)$ 



Points: 5% most central collisions, ALICE [PRL 109, 252301 (2012)] Curves: Our calculation, no hadron rescattering and decays after freeze-out.

#### Harmonic flow coefficients for central collisions

Triangular flow for charged particles



Points: 2% most central collisions, ALICE [PRL 107, 032301 (2011)] Curves: Different maximal resolution  $l_{max}$ 

7. Jet quenching

#### High energetic particles and partons



- At small transverse momenta particle spectra are determined by thermalized medium.
- Physics of high energetic particles and partons is different: they are not thermalized but can be influenced by the medium.

#### Factorization

High energetic processes in hadron collisions are governed by convolution of

- Process-independent parton distribution function: probability to find partons with given momentum in incident hadron.
- Process-dependent hard scattering cross section: probability that initial partons scatter to final state partons with given momenta.
- Process-independent parton fragmentation function: probability that final state partons fragments into a jet with certain hadron content.

# Parton energy loss

Detailed understanding of perturbative QCD constitutes solid foundation to measure changes occurring in heavy ion collisions

- Nuclear PDF's differ from proton PDF's but may be measured by proton-nucleus collisions, electron-nucleus collisions etc.
- Hard scattering cross section not modified by medium if momentum transfer is high enough.
- Key modification: After production, high energetic partons must propagate through hot and dense medium produced in heavy ion collisions.
- By interactions with the gluons and quarks in the medium, high energetic partons transmit part of their energy to the medium.
- Because parton production rates are steeply falling with energy, energy loss leads to a reduction of the number of partons with large energy.

#### Dijets in a heavy ion collision



- One reconstructed jet has large energy, opposing jet has much less energy.
- Transverse energy 205 GeV -70 GeV = 135 GeV must be in soft fragments that cannot be distinguished from background by eye.

#### Dijet asymmetry



- Dijet asymmetry  $A_J = \frac{p_{T,1} p_{T,2}}{p_{T,1} + p_{T,2}}$  between leading and sub-leading jet transverse momentum is larger than in PYTHIA (no jet quenching).
- Effect is larger for more central collisions.
- Significant fraction of  $p_T$  gets transported outside the jet cone by medium.

#### Medium induced gluon radiation

- In perturbative QCD, main parton energy loss mechanism is medium induced gluon radiation. [Baier, Dokshitzer, Mueller, Peigné, Schiff; Zakharov]
- Analogous to bremsstrahlung in QED.
- In vacuum essentially only small angle (colinear) splittings. In medium additional kicks from scattering with medium lead to larger angles.



• Transverse momentum broadening of gluon momentum transverse to quark momentum  $k_{\perp}$  by diffusion / random walk type process

 $rac{d}{dt}\left\langle k_{\perp}^{2}
ight
angle =\hat{q}$  (jet quenching parameter)

• Interactions with medium also induce color decoherence.
#### Monte-Carlo with jet quenching

Monte-Carlo code with jet quenching JEWEL [K. Zapp et al. (2009)] can account for dijet asymmetry  $A_{J}$ 



[S. F., Zapp (2014)]

## $Nuclear\ modification\ factor$

Traditional measure of energy loss is nuclear modification factor

$$R_{AA}^{h}(p_{T},\eta,\text{centrality}) = \frac{\frac{dN_{AA}^{AA} \rightarrow h}{dp_{T}d\eta}}{\langle N_{\text{coll}}^{AA} \rangle \frac{dN_{\text{vacuum}}^{\gamma}}{dp_{T}d\eta}}$$

- Ratio of production cross section for particle *h* in heavy ion (AA) collisions and scaled proton-proton (pp) reference.
- Depends in general on transverse momentum  $p_T$ , rapidity  $\eta$  and centrality but some variables are sometimes integrated over.
- Has been measured for many different particles h.
- In a similar way one defines  $R_{pA}$  for proton ion collisions.

#### Nuclear modification factor for charged particles



[ALICE (2011)]

#### Nuclear modification factor for non-colored particles



- Unidentified charged particles and b-quarks are quenched.
- Photons, W- and Z-bosons are not quenched  $(R_{AA} = 1)$ .

### Nuclear modification factor for jets



• Comparison of proton-Pb collisions  $(R_{pA})$  and Pb-Pb collisions  $(R_{AA})$ .

• No quenching in pA collisions observed.

8. Quarkonia in hot matter

#### Deconfinement and screening

- How can one test deconfinement of quarks and gluons?
- What prevents formation of a meson in a quark-gluon plasma?
- Attractive force between quark and antiquark are screened!



- How close do quark and anti-quark have to be in order for their interaction not to be screened?
- How does this depend on temperature?

It was suggested to investigate these questions for bound states of heavy quark-antiquark pairs (quarkonia) [Matsui, Satz (1986)]

### Quarkonia

Some charmonium states ( $c\bar{c}$  bound states)

- J/ψ(1S) Mass 3.09 GeV
- ψ(2S) Mass 3.69 GeV
- $\chi_{c1}(1\mathsf{P})$  Mass 3.51 GeV
- $\chi_{c2}(1\mathsf{P})$  Mass 3.56 GeV
- . . .

Some bottomonium states ( $b\bar{b}$  bound states)

- $\Upsilon(1S)$  Mass 9.46 GeV
- $\Upsilon(2S)$  Mass 10.02 GeV
- $\Upsilon(3S)$  Mass 10.36 GeV
- . . .

### Sequential suppression (traditional picture)



- Larger mesons or bound states are hindered from binding first, smaller bound states can survive up to higher temperature.
- Heuristic Schrödinger equation approach using screened static quark potentials suggests
  - $J/\psi$  dissociates at  $T_d \approx 2.1 T_c$
  - $\psi(2S)$  is larger and dissociates at  $T_d \approx 1.1 T_c$
  - $\Upsilon(1S)$  dissociates at  $T_d \approx 4 T_c$
  - $\Upsilon(2S)$  is larger and dissociates at  $T_d \approx 1.6 T_c$
  - $\Upsilon(3S)$  is even larger and dissociates at  $T_d\approx 1.2\,T_c$
- In reality, use of static potentials is questionable.

Many effects must be taken into account to properly understand quarkonium in hot matter. Some of them are:

- Cold nuclear matter effects already present for pA collisions.
- Collective dynamics of heavy ion collisions: expansion, flow etc.
- Quarkonia not at rest with respect to medium.
- Formation of quarkonium bound states is purely understood but takes some time. What is influence of medium?
- Recombination of open heavy quarks at hadronization / chemical freeze-out.

Currently no clear picture yet. Experimental and theoretical efforts ongoing.

### Ypsilon suppression



- Excited states of  $\Upsilon$  are clearly suppressed in heavy ion collisions compared to pp collisions at equal energy.
- Does this prove sequential suppression according to Matsui & Satz picture?

### Ypsilon excited states from statistical model



[Andronic (2014)]

- Assumes that  $\Upsilon$  states are generated at chemical freeze-out from available  $b,\,\bar{b}$  quarks.
- Suppression of higher states is due to the Boltzmann factor. Roughly

$$e^{-\frac{M_{\Upsilon(2S)}-M_{\Upsilon(1S)}}{T}} \approx 0.03$$

# 9. Conclusions

#### Conclusions

- We are on the way of understanding the macroscopic material properties of QCD at high temperature and density.
- Relativistic fluid dynamics provides a very good description for the bulk of particles produced in a heavy ion collision as small transverse momentum.
- Heavy ion collisions at RHIC and LHC energies produce a rather strongly coupled liquid with  $\eta/s \approx 0.2$ . New data with improved statistics provide more insights and better constraints.
- High momentum partons loose energy when traversing the dense QCD medium. More detailed understanding from reconstructed jets at the LHC and more detailed data on nuclear modification factors.
- Modifications of heavy quark bound state spectra in heavy ion collisions have been observed both for charm and bottom. Detailed understanding in progress.
- Other interesting topics (initial state physics, photons & di-leptons, low energy run, ...) have been skipped for lack of time.