Phenomenology of heavy-ion collisions

Boris Tomášik

FNSPE, České vysoké učení technické, Praha, Czech Republic
and Univerzita Mateja Bela, Banská Bystrica, Slovakia

boris.tomasik@cern.ch

THOR School
Jahorina, Bosnia and Hercegovina

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The goal of studies with heavy-ion collisions

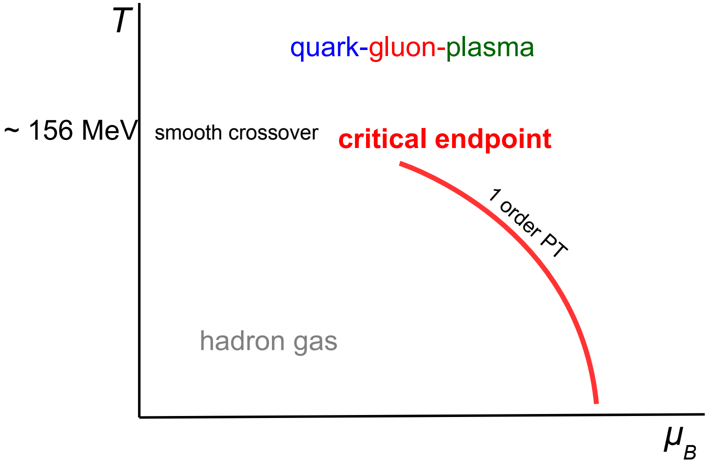
To study the properties of strongly interacting matter in extreme conditions.

- Equation of State
  (complementary to neutron stars and their mergers)
- phase transition(s), critical point
- transport coefficients:
  - shear and bulk viscosity
  - momentum transfer from hard parton to medium ($\hat{q}$)
  - ...

To learn how the created matter looks like

- temperature, pressure, volume, evolution, ...
- vorticity (most vortical fluid)
- emergent hydrodynamics (why hydro works, when it should not)
- ...

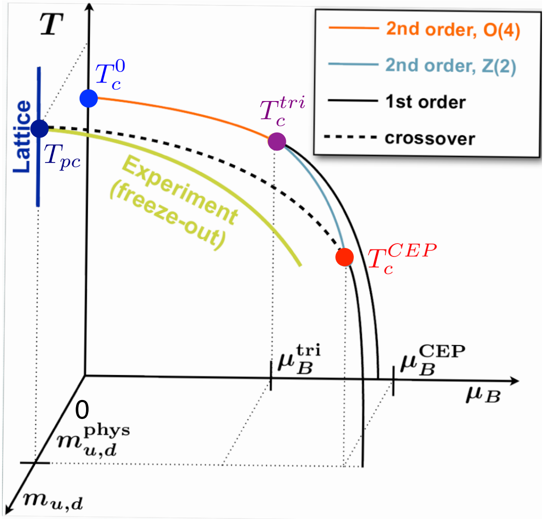
The roadmap for these studies: the phase diagram



μ_B: baryochemical potential

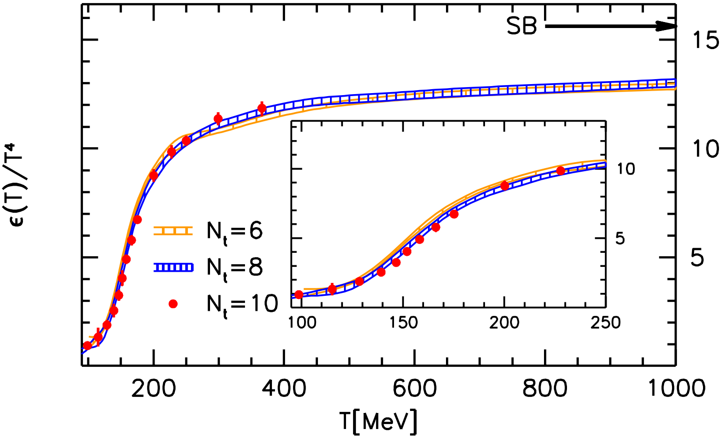
ratio of the numbers of baryons to antibaryons: $B/\bar{B} \propto \exp\left(2\mu_B/T\right)$

The phase diagram: points and transitions



plot: Heng-Tong Ding @ Quark Matter 2019

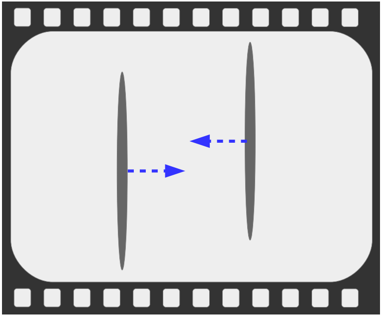
Smooth crossover observed the lattice



[S. Borsanyi, et al., JHEP 11 (2010) 077]

The evolution of a heavy-ion collision 1

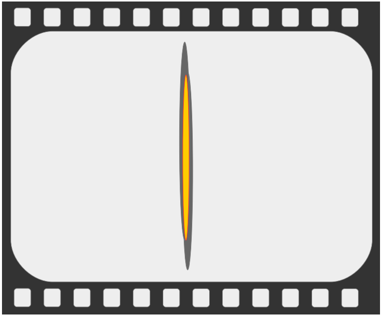
Before the collision



- (highly) Lorentz contracted nuclei approach
  γ between 1 and 2750
- geometry important for later evolution

The evolution of a heavy-ion collision 2

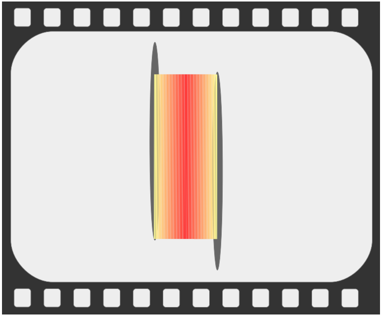
Production of quanta, "energy transformation"



- low $\sqrt{s_{NN}}$
  - low $\sqrt{s_{NN}}$ hadronic mechanisms
  - gradual as nuclei pass through each other
- high $\sqrt{s_{NN}}$
  - partonic, depends on parton distributions
  - nuclear effects on parton distributions
  - quickly emerging hydrodynamics behaviour
- setting up initial conditions for collective behaviour
- crucial for (some of) later correlations

The evolution of a heavy-ion collision 3

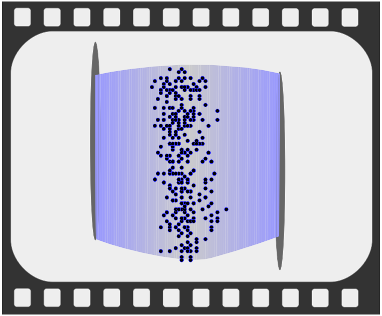
Flowing of hot (deconfined) matter



- expansion!
- (s)QGP for $\sqrt{s_{NN}}$ above ...
- (surprisingly) well described by hydrodynamic models (particularly if long in the QGP phase)
- properties of matter clearly enter modelling
  - Equation of State
  - viscosities

The evolution of a heavy-ion collision 4

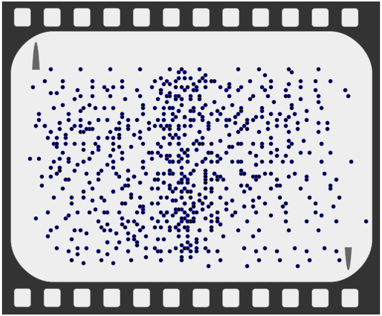
Hadronisation and hadron gas



- chemical freeze-out happens here
- gas of interacting hadrons and resonances (HRG)
- suitably described by transport models
- continues the strong expansion
- seems to start in chemical equilibrium and get out of this equilibrium
- acts like "firewall" for the deconfined fireball

The evolution of a heavy-ion collision 5

Freeze-out



- Hadrons produced with their final state momenta and correlations
- Happens gradually
- sometimes modelled as sudden process (Cooper-Frye formalism)

The evolution of heavy-ion collision: summary

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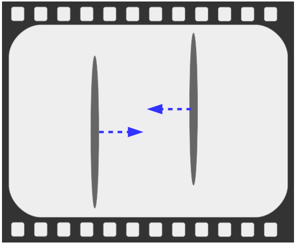
1. Before the collision



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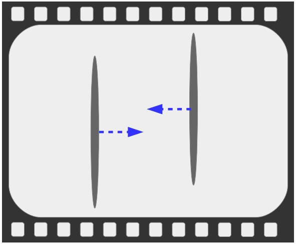
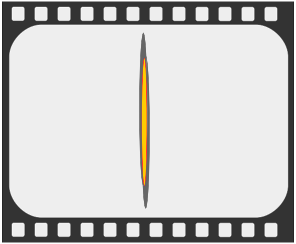


2. Production of quanta



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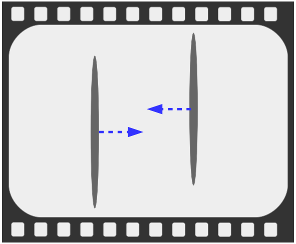

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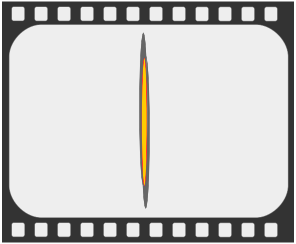
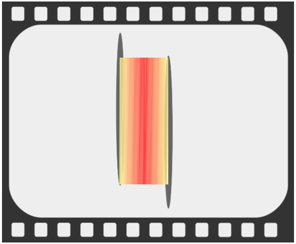


3. QGP



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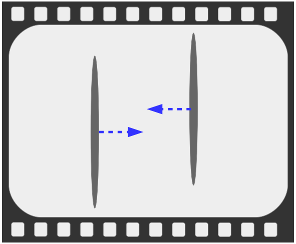

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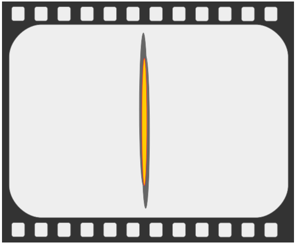

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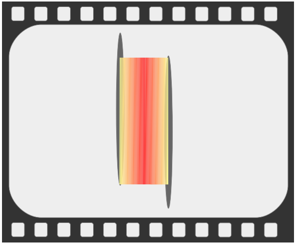

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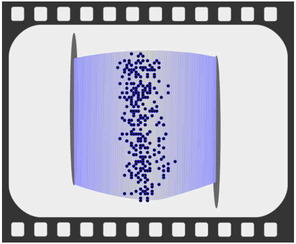

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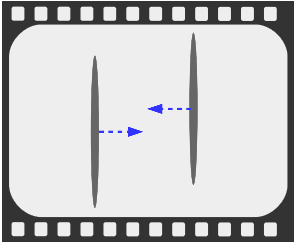

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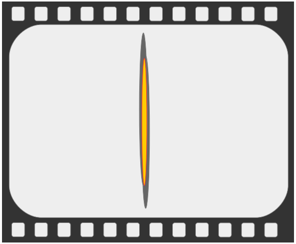

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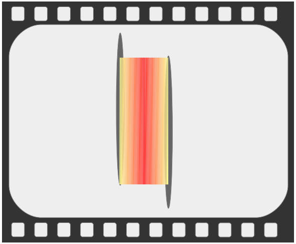

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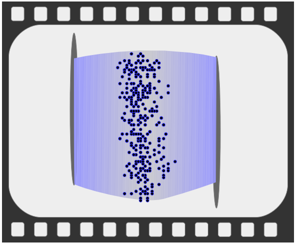
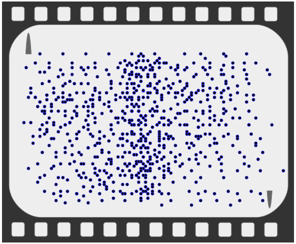
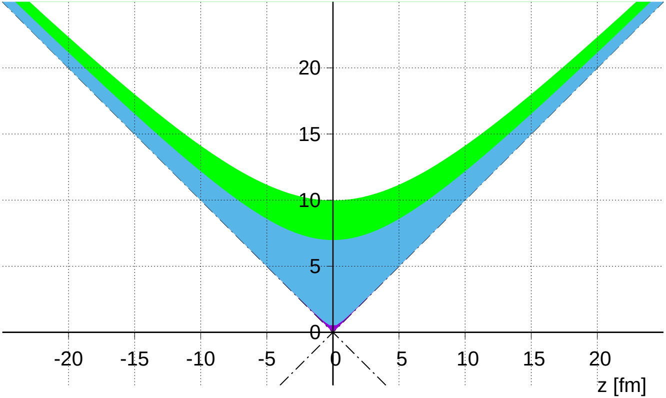


5. Freeze-out



The space-time diagram of the evolution

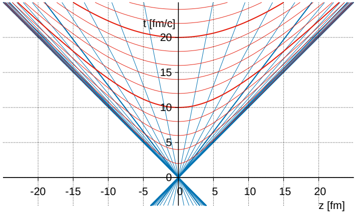


Space-time parametrisation: the Milne coordinates

More suitable for longitudinally rapidly expanding systems:

longitudinal proper time

$$\tau = \sqrt{t^2 - z^2}$$

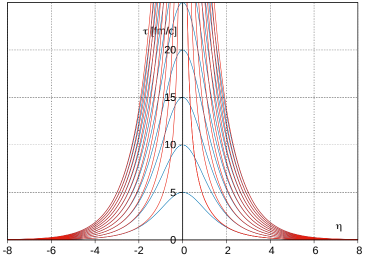


space-time rapidity

$$\eta = \frac{1}{2} \ln \frac{t+z}{t-z}$$

Inverse transformation

$$\begin{aligned} t &= \tau \cosh \eta \\ z &= \tau \sinh \eta \end{aligned}$$



Momentum parametrisation

4-momentum of a particle with the mass m:

- transverse momentum p_t
- azimuthal angle ϕ
- transverse mass

$$m_t = \sqrt{m^2 + p_t^2}$$

- rapidity

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$$

Momentum parametrisation:

$$p = (E, \vec{p}) = (m_t \cosh y, p_t \cos\phi, p_t \sin\phi, m_t \sinh y)$$

Experimental proxy for the rapidity: pseudorapidity (same letter η used :-( )

$$\eta = \frac{1}{2} \ln \frac{|p| + p_z}{|p| - p_z} = -\ln \tan \frac{\theta}{2}$$

easy to measure, since θ is the angle between $\vec{p}$ and the beam
good approximation for $|p| \gg m$

Typical energies, sizes, times

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- energy of central collision of Pb+Pb at the LHC (CERN): $208 \times 5.5 = 1144\,\mathrm{TeV} \approx 0{,}2\,\mathrm{mJ}$ (energy of a flying hornet)

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- typical size of the fireball: 10^{-14} m (10 fm)
  (If QGP were as big as poppy seed, poppy seed would be as big as the Earth.)

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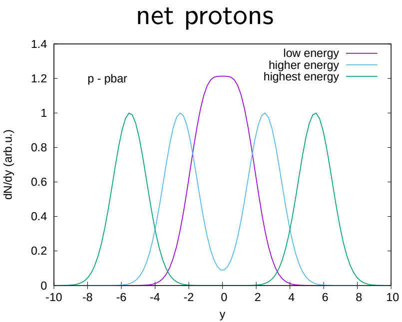
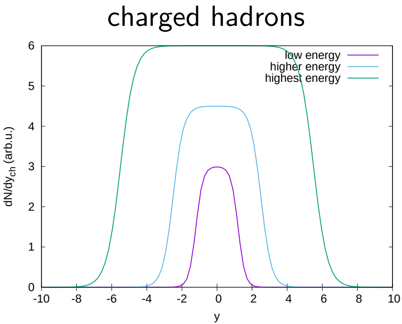
- typical size of the fireball: 10^{-14} m (10 fm)
  (If QGP were as big as poppy seed, poppy seed would be as big as the Earth.)

- typical lifetime of the fireball: 10^{-22} s (10 fm/c)
  (The time it takes for the light to pass through a nucleus.)

Collisions at different energies

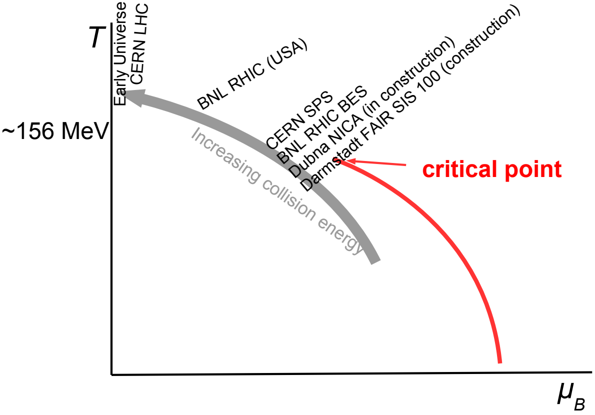




- Incoming baryon number is somewhat stopped with respect to beam rapidity.
- At sufficient energies, produced hadrons exhibit plateau in rapidity.

Mapping the phase diagram

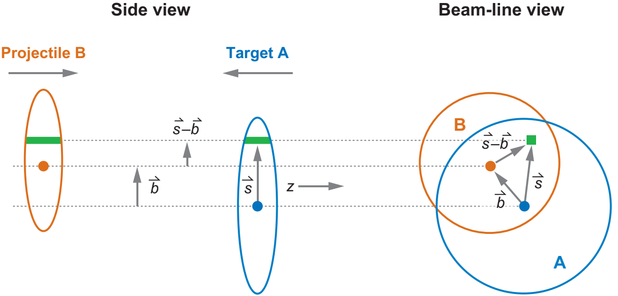
conserved quantity: $B - \bar{B}$
higher collision energy $\Rightarrow$ higher pair production $B\bar{B}$
$\Rightarrow$ smaller $B/\bar{B}$ $\Rightarrow$ smaller μ_B



μ_B also depends on rapidity

Centrality

- Each collision happens at different impact parameter b.
- Impact parameter b is not measurable.
- Nevertheless, b influences the geometry and future evolution



spectators: nucleons that did *not* interact

participants: nucleons that did interact

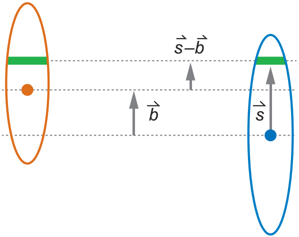
wounded nucleons: nucleons that did interact *inelastically*

figure: M.L. Miller, K. Reygers, S.J. Sanders, P. Steinberg, Ann. Rev. Nucl. Part. Sci. 57 (2007) 205

Optical Glauber model

Projected nuclear density

$$\hat{T}_A(\vec{s}) = \int \hat{\rho}(\vec{s}, z_A) dz_A$$

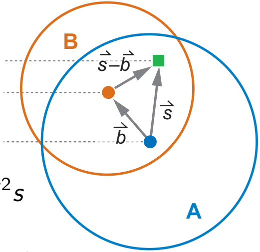


Overlap function

$$\hat{T}_{AB}(\vec{s}) = \int \hat{T}_A(\vec{s})\vec{T}_B(\vec{s}-\vec{b})d^2s$$

Number of binary NN collisions

$$N_{coll}(\vec{s}) = ABT_{AB}(\vec{s})\sigma_{inel}^{NN}$$



Number of wounded nucleons

$$N_w(\vec{s}) = A\int \hat{T}_A(\vec{s})\left\{1-\left[1-\hat{T}_B(\vec{s}-\vec{b})\sigma_{inel}^{NN}\right]^B\right\}d^2s + B\int \hat{T}_B(\vec{s}-\vec{b})\left\{1-\left[1-\hat{T}_A(\vec{s})\sigma_{inel}^{NN}\right]^A\right\}d^2s$$

Even at the same $\vec{s}$ the numbers of NN collisions will fluctuate.

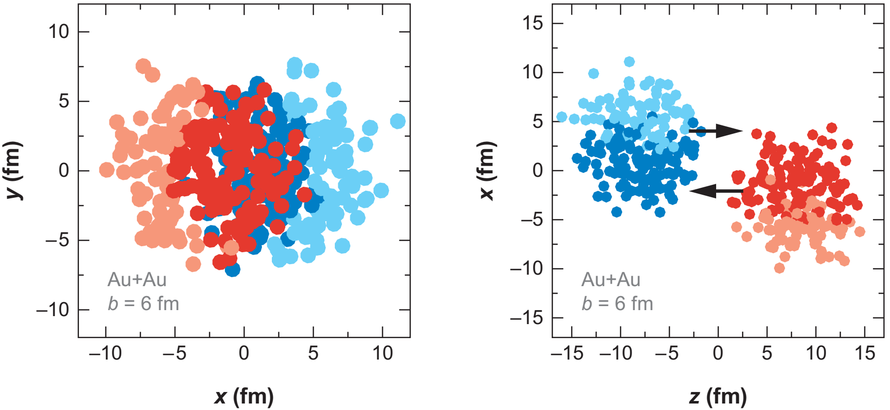
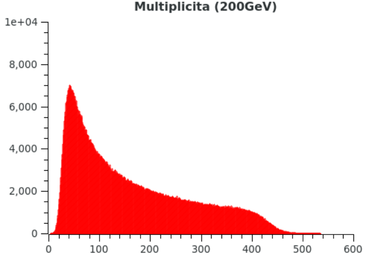
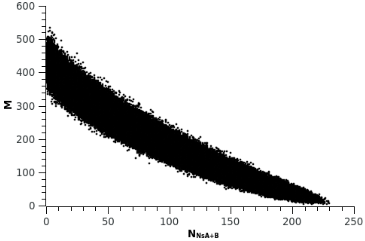


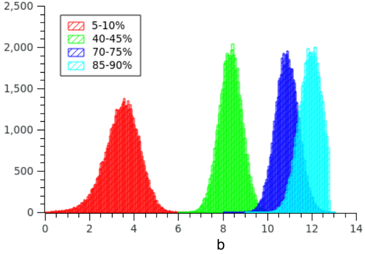
figure: M.L. Miller, K. Reygers, S.J. Sanders, P. Steinberg, Ann. Rev. Nucl. Part. Sci. 57 (2007) 205

Experimental determination of centrality

Multiplicity: $M \propto \left(\frac{1-\alpha}{2} N_w + \alpha N_{coll}\right)$
(α determined to fit centrality depence of multiplicity)
Use measurable quantities: M, N_{spect}, number of spectator neutrons







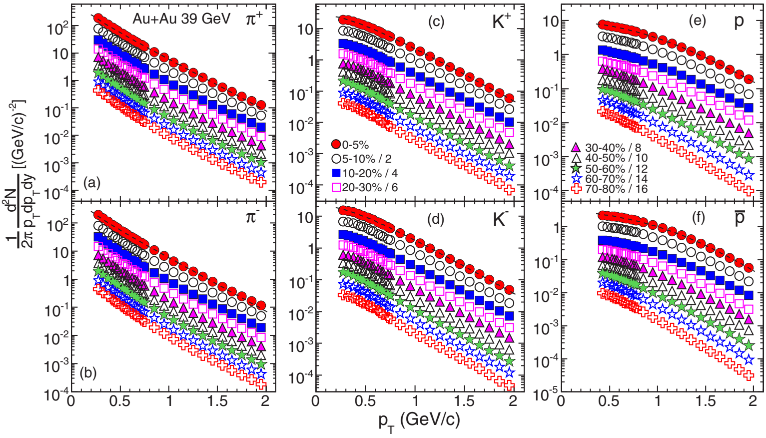
[simulations Matěj Gajdoš, Grammar School Ustí nad Labem]

Observables: hadrons from the bulk fireball

Distribution of hadrons

We can obtain temperature at the kinetic freeze-out and the expansion velocity from transverse momentum spectra.

Example:



[STAR collaboration, Phys. Rev. C 96 (2017) 044904]

Thermal equilibrium in longitudinally expanding fireball

Emission function (pre-blast-wave model)

- longitudinal boost invariance $u^\mu = \gamma(1,0,0,z/t) = (\cosh\eta, 0, 0, \sinh\eta)$
- surface of the cross-cut S
- integrate over all coordinates η
- energy of hadron in the fluid rest frame

$$E^* = p^\mu u_\mu = m_t \cosh y \cosh\eta - m_t \sinh y \sinh\eta = m_t \cosh(\eta - y)$$

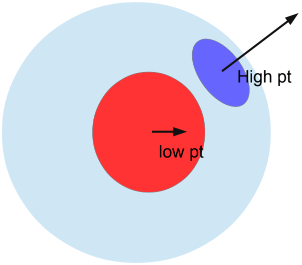
$$\begin{aligned}\frac{dN}{m_t dm_t} &\propto S\int_{-\infty}^{\infty} \tau d\eta\, m_t \cosh(\eta-y) \exp\left(-\frac{p^\mu u_\mu}{T}\right)\\ &= S\int_{-\infty}^{\infty} \tau d\eta\, m_t \cosh(\eta-y) \exp\left(-\frac{m_t\cosh(\eta-y)}{T}\right)\\ &= S\tau m_t K_1\left(\frac{m_t}{T}\right)\end{aligned}$$

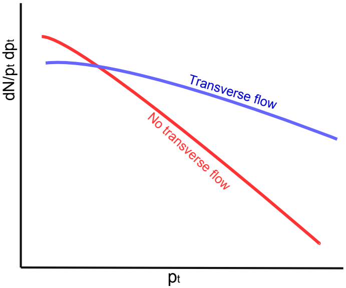
Scaling in m_t!

Spectra from transversely expanding fireball

Hadrons for a given p_t are produced by corresponding *region of homogeneity*.

This enhances production of higher p_t, i.e. shorter wavelength = blue shift





$T^* \approx T + m\langle v_t \rangle \Rightarrow$ obtain T and $\langle v_t \rangle$ from spectra of different sorts of identified particles

A simple formula for p_t spectra—blast-wave model

Transverse flow velocity $v_t(r) = \tanh\eta_t(r)$

$$u^\mu = \left(\cosh\eta\cosh\eta_t(r), \cos\psi\sinh\eta_t(r), \sin\psi\sinh\eta_t(r), \sinh\eta\cosh\eta_t(r)\right)$$

Energy in the fluid rest frame

$$E^* = p^\mu u_\mu = m_t\cosh(\eta - y)\cosh\eta_t(r) - p_t\sinh\eta_t(r)\cos(\phi - \psi)$$

Transverse momentum spectrum

$$\frac{dN}{m_t dm_t}$$

$$\propto \int_{-\infty}^{\infty}\tau d\eta\int_0^R r\,dr\;\int_0^{2\pi} d\psi\, m_t\cosh(\eta - y)\,\Theta(R - r)\,\exp\left(-\frac{p^\mu u_\mu}{T}\right)$$

$$= 2\pi\tau m_t\int_0^R r\,dr\,K_1\left(\frac{m_t\cosh\eta_t(r)}{T}\right) I_0\left(\frac{p_t\sinh\eta_t(r)}{T}\right)$$

Resonance contributions are missing here!

Analysis of the kinetic freeze-out

[I. Melo, B. Tomášik, J. Phys. G to appear, arXiv:1908.03023 [nucl-th]]

- a fit with the blast-wave model

$$S(x,p)\,d^4x = g_i\,\frac{m_t\;\cosh(\eta-y)}{(2\pi)^3}\left(\exp\left(\frac{p_\mu u^\mu - \mu_i}{T_k}\right)+s_i\right)^{-1}$$
$$\theta\left(1-\frac{r}{R}\right)\times r\,dr\,d\varphi\,\delta(\tau-\tau_0)\,\tau\,d\tau\,d\eta$$

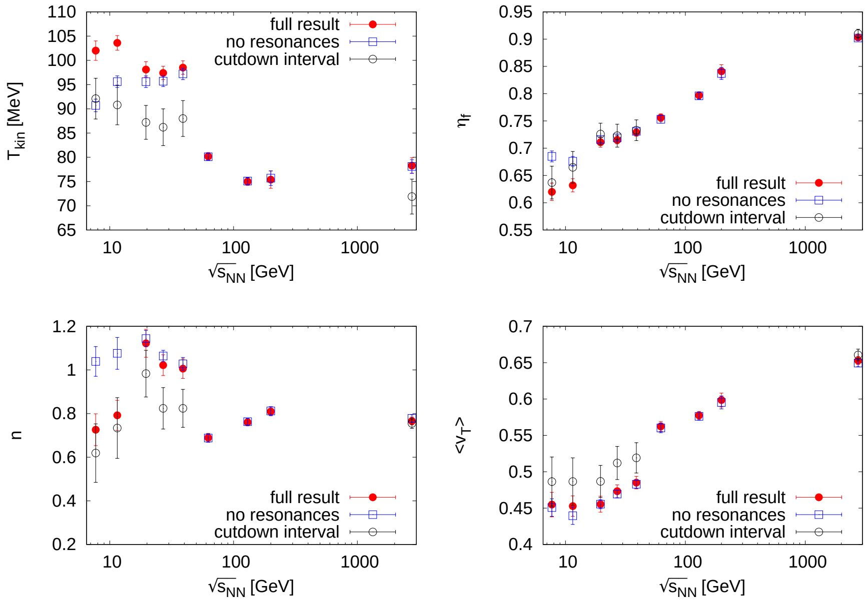
$$E\frac{d^3N}{dp^3} = \int_\Sigma S(x,p)\,d^4x$$

- transverse velocity

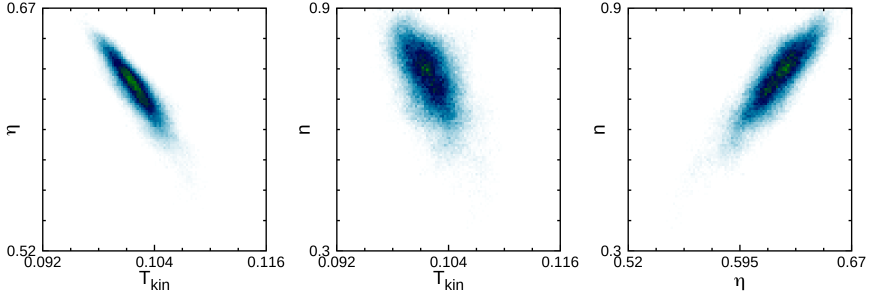
$$v_t = \tanh\eta_t = \eta_f\left(\frac{r}{R}\right)^n$$

- contributions from resonance decays included
- partial chemical equilibrium:
  chemical potentials for each species

Excitation functions of the freeze-out parameters



The parameters are correlated

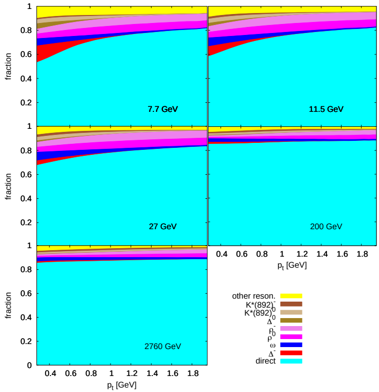


$$\sqrt{s_{NN}} = 7.7\,\mathrm{GeV}$$

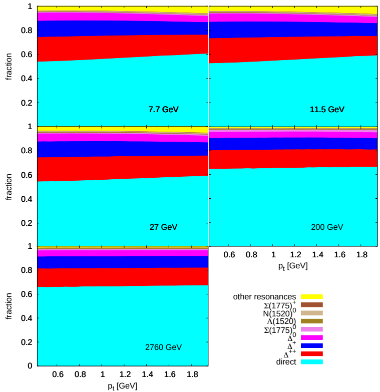
Contributions from the resonances

Relative contributions to p_t spectra

pions



protons



Azimuthal anisotropy of hadronic momentum distributions

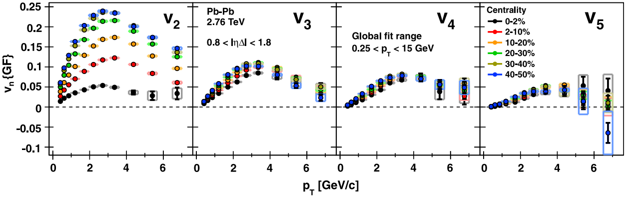
- parametrized by Fourier expansion

$$\frac{dN}{p_t\, dp_t\, dy\, d\phi} = \frac{1}{2\pi}\frac{dN}{p_t\, dp_t\, dy}\left(1 + 2\sum_{n=1}^{\infty} v_n(p_t, y)\cos\left(n(\phi - \phi_n)\right)\right)$$

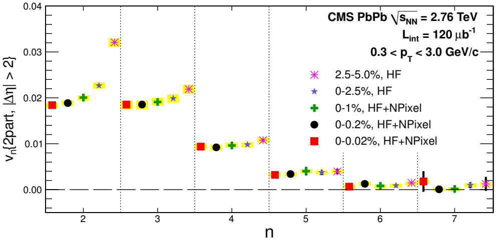
- summation over many events in symmetric collisions at midrapidity
  $\Rightarrow$ symmetry constraints: $\phi_n = 0$, $n = 2, 4, 6, \ldots$

- all v_n's non-vanishing in individual events
- may be a result of stronger blueshift in some directions

Examples of data



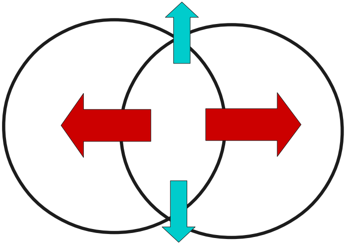
[ALICE collab: Phys. Lett. B **708** (2012) 249]

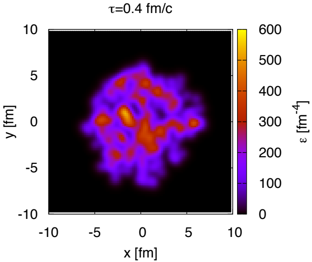


[CMS collab: JHEP 02 (2014) 088]

From azimuthal anisotropy to momentum anisotropy

- expansion accelerates due to pressure gradients
- higher $\nabla p \Rightarrow$ stronger expansion
- response to pressure: depends on EoS and transport coefficients
- inhomogeneities in real collisions due to event-by-event fluctuations





[B. Schenke, S. Jeon, C. Gale, PRL106 (2011) 042301]

Summary

- we can map the QCD phase diagram with colliding nuclei at different energies
- gross features of particle production are statistical
- expansion, including its anisotropies, can be mapped via hadron distributions
- this brings us to study the properties of QCD matter