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Particle momentum spectra and correlations from quasi equilibrium state of expanding quantum fields

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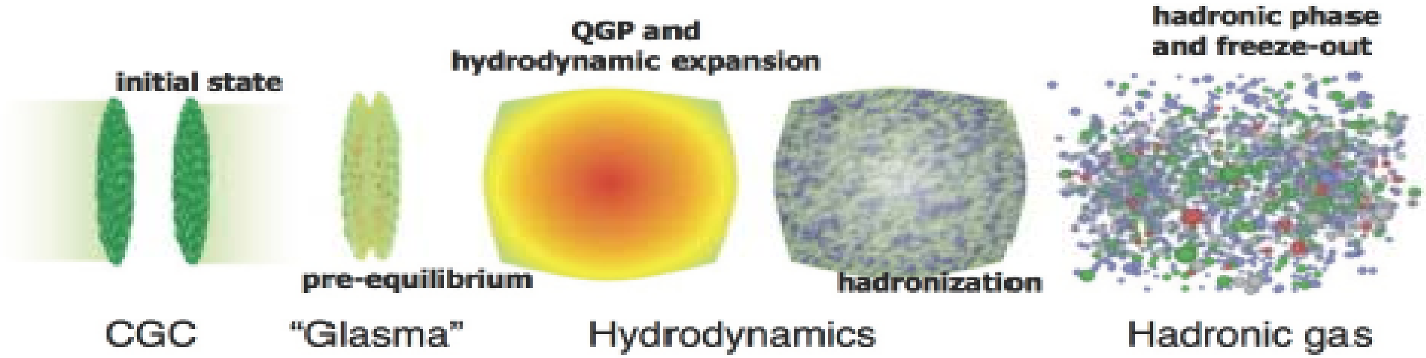
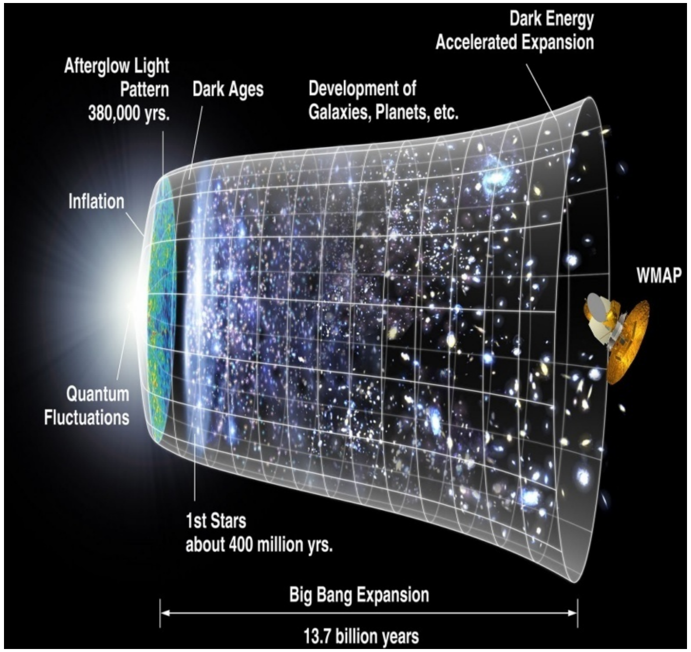
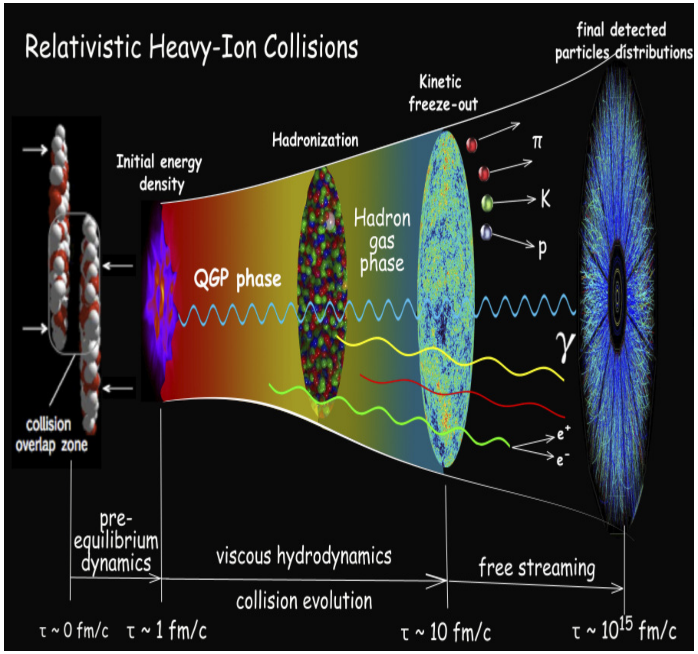
Ultrarelativistic heavy ion collision of the two Lorentz contracted nuclei takes place in restricted spacetime region and produces initially very dense quark gluon matter which then expands (merely in the longitudinal direction) and eventually undergoes a transition to hadrons

Successive stages of the ``Little Bang"



Big Bang (curved spacetime)
and
Little Bang (flat spacetime)

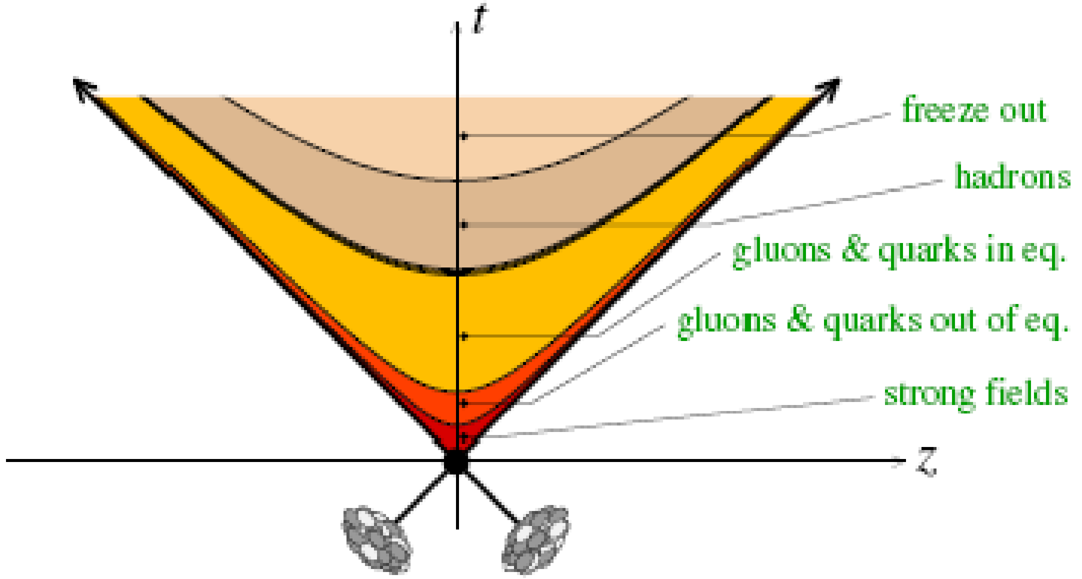




Ultrarelativistic heavy ion collisions
produce a quark-gluon matter which lies in the future light cone originating from given points on the t = z = 0 plane of

the Minkowski spacetime manifold.

The space–time picture of a relativistic heavy ion collision is naturally described in the curved coordinate system



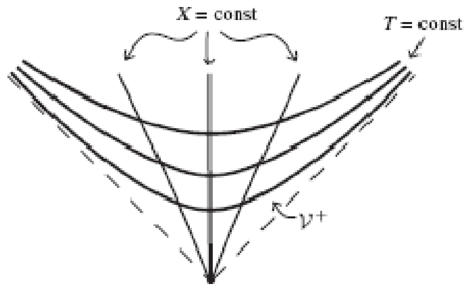
$$\tau = \sqrt{t^2 - z^2}$$

Initial (as well as final) conditions are defined at $\tau = const$

Quasi equilibrium statistical operator and reduced description

Non-equilibrium QFT (Heisenberg representation):

$$n_\mu(x)\langle T^{\mu\nu}(x)\rangle_{i.s.}$$



Quasi equilibrium statistical operator (and hydro):

$$\rho_\sigma = Z_\sigma^{-1} \exp\left(-\int_{\sigma_\nu} d\sigma n_\nu(x)\beta(x)u_\mu(x)T^{\mu\nu}(x)\right)$$

$$Tr[\rho_\sigma] = 1$$

$$\beta(x)u_\mu(x):\ n_\mu(x)\langle T^{\mu\nu}(x)\rangle_{i.s.} = n_\mu(x)Tr[\rho_\sigma T^{\mu\nu}(x)]$$

Reduced description (Heisenberg representation): $\langle\widehat{O}(\sigma)\rangle = Tr[\rho_\sigma\widehat{O}(\sigma)]$

Freeze-out (sudden) at σ_{fin} : $\langle\widehat{O}(\sigma>\sigma_{fin})\rangle = Tr[\rho_{\sigma_{fin}}\widehat{O}(\sigma>\sigma_{fin})]$

Exactly solvable toy-model

Non-interacting scalar field

$$S = \int dt d^3 r \left[\frac{1}{2} \left(\frac{\partial \phi}{\partial t} \right)^2 - \frac{1}{2} \left(\frac{\partial \phi}{\partial \mathbf{r}} \right)^2 - \frac{m^2}{2} \phi^2 \right] \equiv \int dt d^3 r L$$

Energy-momentum tensor

$$T^{\mu\nu}(x) = \partial^\mu \phi \partial^\nu \phi - g^{\mu\nu} L$$

Boost-invariant expansion

$$n^\mu(x) = u^\mu(x) = (\cosh \eta, 0, 0, \sinh \eta)$$

$$t = \tau \cosh \eta, \qquad z = \tau \sinh \eta \qquad \tau = \sqrt{t^2 - z^2}$$

$$\sigma_\nu : \tau = const$$

Quasi equilibrium statistical operator of the toy-model

$$n_\mu u_\nu T^{\mu\nu}(x) = \frac{1}{2}\left(\frac{\partial\phi}{\partial\tau}\right)^2 + \frac{1}{2}\frac{1}{\tau^2}\left(\frac{\partial\phi}{\partial\eta}\right)^2 + \frac{1}{2}\left(\frac{\partial\phi}{\partial\mathbf{r}_T}\right)^2 + \frac{1}{2}m^2\phi^2$$

$$H^{[\tau]} = \int_{\sigma_\nu} d\sigma n_\nu(x) u_\mu(x) T^{\mu\nu}(x) \qquad d\sigma = \tau d\eta dr_x dr_y$$

$$\rho = Z^{-1}\exp\left(-\beta H^{[\tau]}\right) \qquad \beta = 1/T = const$$

Ground-state (when $\beta \to \infty$) corresponds to lowest

energy eigenstate of $H^{[\tau]} \neq H^{[t]} = \int dxdydz T^{00}(x)$

$\tau' > \tau$ Klein-Gordon equation $(\partial_\mu\partial^\mu + m^2)\phi(x) = 0$

One-particle momentum spectra: $\langle a^\dagger(\mathbf{p})a(\mathbf{p})\rangle = Tr[\rho a^\dagger(\mathbf{p})a(\mathbf{p})]$

particles and quasiparticles

$$\phi(x) = \int \frac{d^3p}{\sqrt{2\omega_p}} \frac{1}{(2\pi)^{3/2}} \left(e^{-i\omega_p t + i\mathbf{pr}} a(\mathbf{p}) + e^{i\omega_p t - i\mathbf{pr}} a^\dagger(\mathbf{p}) \right)$$

where $\omega_p = \sqrt{\mathbf{p}^2 + m^2}$ $\qquad [a(\mathbf{p}), a^\dagger(\mathbf{p}')] = \delta^{(3)}(\mathbf{p} - \mathbf{p}')$

Non-diagonal representation of $H^{[\tau]}$!

$$z = \tau \sinh \eta \qquad \omega_p = m_T \cosh \theta$$
$$t = \tau \cosh \eta \qquad p_z = m_T \sinh \theta$$

$$\phi(x) = \int_{-\infty}^{+\infty} \frac{d^2 p_T d\mu}{4\pi\sqrt{2}} [-i \exp(\mu\pi/2 + i\mu\eta + i\mathbf{p}_T\mathbf{r}_T) H_{i\mu}^{(2)}(m_T\tau) b(\mathbf{p}_T, \mu) +$$

$$i \exp(-\mu\pi/2 - i\mu\eta - i\mathbf{p}_T\mathbf{r}_T) H_{i\mu}^{(1)}(m_T\tau) b^\dagger(\mathbf{p}_T, \mu)]$$

$$[b(\mathbf{p}_T, \mu), b^\dagger(\mathbf{p}'_T, \mu')] = \delta(\mu - \mu')\delta^{(2)}(\mathbf{p}_T - \mathbf{p}'_T)$$

$$\alpha(\mathbf{p}_T, \theta) = (m_T \cosh\theta)^{1/2} a(\mathbf{p}), \qquad \alpha(\mathbf{p}_T, \theta) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} e^{i\mu\theta} b(\mathbf{p}_T, \mu) d\mu,$$
$$\alpha^\dagger(\mathbf{p}_T, \theta) = (m_T \cosh\theta)^{1/2} a^\dagger(\mathbf{p}) \qquad \alpha^\dagger(\mathbf{p}_T, \theta) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} e^{-i\mu\theta} b^\dagger(\mathbf{p}_T, \mu) d\mu$$

The same vacuum state for a and b particles

Quasi equilibrium statistical operator: diagonalization

$$H^{[\tau]} = \int_{-\infty}^{+\infty} d^2p_T d\mu \tfrac{1}{2}\omega(p_T,\mu)\times$$
$$[E(p_T,\mu)(b^\dagger(\mathbf{p}_T,\mu)b(\mathbf{p}_T,\mu)+b(\mathbf{p}_T,\mu)b^\dagger(\mathbf{p}_T,\mu))-$$
$$F(p_T,\mu)b(\mathbf{p}_T,\mu)b(-\mathbf{p}_T,-\mu)-F^*(p_T,\mu)b^\dagger(\mathbf{p}_T,\mu)b^\dagger(-\mathbf{p}_T,-\mu)]$$

$$E(p_T,\mu) = \frac{\pi\tau}{4\omega(p_T,\mu)}$$
$$\left[|\partial_\tau \widetilde{H}^{(2)}_{i\mu}(m_T\tau)|^2 + \omega^2(p_T,\mu)|\widetilde{H}^{(2)}_{i\mu}(m_T\tau)|^2\right]$$
$$F(p_T,\mu) = \frac{\pi\tau}{4\omega(p_T,\mu)}$$
$$\left[(\partial_\tau \widetilde{H}^{(2)}_{i\mu}(m_T\tau))^2 + \omega^2(p_T,\mu)(\widetilde{H}^{(2)}_{i\mu}(m_T\tau))^2\right]$$

$$\widetilde{H}^{(1)}_{i\mu}(m_T\tau) = \exp(-\pi\mu/2)H^{(1)}_{i\mu}(m_T\tau)$$
$$\widetilde{H}^{(2)}_{i\mu}(m_T\tau) = \exp(\pi\mu/2)H^{(2)}_{i\mu}(m_T\tau)$$

$$\omega(p_T,\mu) = \sqrt{m_T^2 + \frac{\mu^2}{\tau^2}}$$

Quasi equilibrium statistical operator: diagonalization

Using Bogolyubov transformation

$$b(\mathbf{p}_T,\mu) = \alpha(\mathbf{p}_T,\mu,\tau)\xi(\mathbf{p}_T,\mu,\tau)+\beta^*(\mathbf{p}_T,\mu,\tau)\xi^\dagger(-\mathbf{p}_T,-\mu,\tau)$$
$$b^\dagger(\mathbf{p}_T,\mu) = \alpha^*(\mathbf{p}_T,\mu,\tau)\xi^\dagger(\mathbf{p}_T,\mu,\tau)+\beta(\mathbf{p}_T,\mu,\tau)\xi(-\mathbf{p}_T,-\mu,\tau)$$

$$|\alpha(\mathbf{p}_T,\mu,\tau)|^2 - |\beta(\mathbf{p}_T,\mu,\tau)|^2 = 1$$
$$\xi(\mathbf{p}_T,\mu,\tau)|0,\tau\rangle = 0$$
$$b(\mathbf{p}_T,\mu)|0\rangle = 0$$
$$|0,\tau\rangle \neq |0\rangle$$

one can finally get diagonal representation

$$H^{[\tau]} = \int_{-\infty}^{+\infty} d^2p_T d\mu \tfrac{1}{2}\omega(p_T,\mu)\xi^\dagger(\mathbf{p}_T,\mu)\xi(\mathbf{p}_T,\mu) \; + c-number$$

Charged pions (say, π^+):

$$\langle a_+^\dagger(\mathbf{p}_1)a_+(\mathbf{p}_2)\rangle = Tr[\rho a_+^\dagger(\mathbf{p}_1)a_+(\mathbf{p}_2)]$$
$$\langle a_+^\dagger(\mathbf{p}_1)a_+^\dagger(\mathbf{p}_2)a_+(\mathbf{p}_1)a_+(\mathbf{p}_2)\rangle = Tr[\rho a_+^\dagger(\mathbf{p}_1)a_+^\dagger(\mathbf{p}_2)a_+(\mathbf{p}_1)a_+(\mathbf{p}_2)]$$

$$a_+(\mathbf{p}) = \frac{1}{\sqrt{2}}(a_1(\mathbf{p}) + ia_2(\mathbf{p})),$$
$$a_+^\dagger(\mathbf{p}) = \frac{1}{\sqrt{2}}(a_1^\dagger(\mathbf{p}) - ia_2^\dagger(\mathbf{p}))$$

$$\rho = Z^{-1}\exp\left(-\beta(H_1^{[\tau]} + H_2^{[\tau]} + H_3^{[\tau]})\right)$$

$$\langle a_+^\dagger(\mathbf{p})a_+^\dagger(\mathbf{p})\rangle = \langle a_+(\mathbf{p})a_+(\mathbf{p})\rangle = 0 \qquad \langle a_+^\dagger(\mathbf{p})\rangle = \langle a_+(\mathbf{p})\rangle = 0$$

$$\langle a_1^\dagger(\mathbf{p})a_1^\dagger(\mathbf{p})\rangle = \langle a_2^\dagger(\mathbf{p})a_2^\dagger(\mathbf{p})\rangle = \langle a_3^\dagger(\mathbf{p})a_3^\dagger(\mathbf{p})\rangle \neq 0$$

$$\langle a_1(\mathbf{p})a_1(\mathbf{p})\rangle = \langle a_3(\mathbf{p})a_2(\mathbf{p})\rangle = \langle a_2(\mathbf{p})a_3(\mathbf{p})\rangle \neq 0$$

$$\langle a_1(\mathbf{p})\rangle = \langle a_1^\dagger(\mathbf{p})\rangle = \dots = 0$$

Charged pions:

$$\langle a_+^\dagger(\mathbf{p}_1)a_+(\mathbf{p}_2)\rangle = \langle a^\dagger(\mathbf{p}_1)a(\mathbf{p}_2)\rangle$$

$$\langle a_+^\dagger(\mathbf{p}_1)a_+^\dagger(\mathbf{p}_2)a_+(\mathbf{p}_1)a_+(\mathbf{p}_2)\rangle =$$
$$\langle a^\dagger(\mathbf{p}_1)a(\mathbf{p}_1)\rangle\langle a^\dagger(\mathbf{p}_2)a(\mathbf{p}_2)\rangle+\langle a^\dagger(\mathbf{p}_1)a(\mathbf{p}_2)\rangle\langle a^\dagger(\mathbf{p}_2)a(\mathbf{p}_1)\rangle$$

$$\langle a_1^\dagger(\mathbf{p}_1)a_1(\mathbf{p}_2)\rangle = \langle a_2^\dagger(\mathbf{p}_1)a_2(\mathbf{p}_2)\rangle = \langle a_3^\dagger(\mathbf{p}_1)a_3(\mathbf{p}_2)\rangle \equiv \langle a^\dagger(\mathbf{p}_1)a(\mathbf{p}_2)\rangle$$

Two-particle correlation function (without Coulomb FSI): $\mathbf{p} = (\mathbf{p}_1 + \mathbf{p}_2)/2$, $\mathbf{q} = \mathbf{p}_2 - \mathbf{p}_1$

$$C(\mathbf{p},\mathbf{q}) = \frac{\langle a_+^\dagger(\mathbf{p}_1)a_+^\dagger(\mathbf{p}_2)a_+(\mathbf{p}_1)a_+(\mathbf{p}_2)\rangle}{\langle a_+^\dagger(\mathbf{p}_1)a_+(\mathbf{p}_1)\rangle\langle a_+^\dagger(\mathbf{p}_2)a_+(\mathbf{p}_2)\rangle} = 1 + \frac{\langle a^\dagger(\mathbf{p}_1)a(\mathbf{p}_2)\rangle\langle a^\dagger(\mathbf{p}_2)a(\mathbf{p}_1)\rangle}{\langle a^\dagger(\mathbf{p}_1)a(\mathbf{p}_1)\rangle\langle a^\dagger(\mathbf{p}_2)a(\mathbf{p}_2)\rangle}$$

Particle momentum spectra (exact expressions):

$$\langle a_+^\dagger(\mathbf{p}_1)a_+(\mathbf{p}_2)\rangle = \frac{\delta^{(2)}(\mathbf{p}_{T1}-\mathbf{p}_{T2})}{2\pi\sqrt{\omega_{p1}\omega_{p2}}}\int_{-\infty}^{+\infty} d\mu_1 e^{-i\mu_1(\theta_1-\theta_2)}\times$$

$$\left[\frac{1}{e^{\beta\omega(p_{T1},\mu_1)}-1}\left(1+2|\beta(p_{T1},\mu_1,\tau)|^2\right)+|\beta(p_{T1},\mu_1,\tau)|^2\right]$$

$$|\beta(p_T,\mu,\tau)|^2 = \frac{E-1}{2}$$

$$\omega(p_T,\mu) = \sqrt{m_T^2+\frac{\mu^2}{\tau^2}}$$

$$E(p_T,\mu) = \frac{\pi\tau}{4\omega(p_T,\mu)}\times$$

$$\left[|\partial_\tau \widetilde{H}_{i\mu}^{(2)}(m_T\tau)|^2+\omega^2(p_T,\mu)|\widetilde{H}_{i\mu}^{(2)}(m_T\tau)|^2\right]$$

$$\widetilde{H}_{i\mu}^{(1)}(m_T\tau) = \exp(-\pi\mu/2)H_{i\mu}^{(1)}(m_T\tau)$$

$$\widetilde{H}_{i\mu}^{(2)}(m_T\tau) = \exp(\pi\mu/2)H_{i\mu}^{(2)}(m_T\tau)$$

One-particle momentum spectra ($\delta^{(2)}(0) \rightarrow (2\pi)^{-2} R_T^2$) :

$$\langle a_+^\dagger(\mathbf{p}) a_+(\mathbf{p}) \rangle = \frac{R_T^2}{(2\pi)^3 \omega_p} \int_{-\infty}^{+\infty} d\mu \times$$
$$\left[\frac{1}{e^{\beta\omega(p_T,\mu)} - 1} \left(1 + 2|\beta(p_T,\mu,\tau)|^2\right) + |\beta(p_T,\mu,\tau)|^2 \right]$$

induced radiation

spontaneous radiation

Creation from the "vacuum" :

$$\langle 0,\tau | a_+^\dagger(\mathbf{p}) a_+(\mathbf{p}) | 0,\tau \rangle = \frac{R_T^2}{(2\pi)^3 \omega_p} \int_{-\infty}^{+\infty} d\mu |\beta(p_T,\mu,\tau)|^2$$

One-particle momentum spectra and Bose-Einstein local equilibrium distribution function of the ideal gas:

$$\langle a_+^\dagger(\mathbf{p})a_+(\mathbf{p})\rangle = \langle a_+^\dagger(\mathbf{p})a_+(\mathbf{p})\rangle_{l.eq.} + \langle a_+^\dagger(\mathbf{p})a_+(\mathbf{p})\rangle_{cond}$$

$$\langle a_+^\dagger(\mathbf{p})a_+(\mathbf{p})\rangle_{cond} = \frac{R_T^2}{(2\pi)^3\omega_p}\int_{-\infty}^{+\infty} d\mu|\beta(p_T,\mu,\tau)|^2\left[\frac{2}{e^{\beta\omega(p_T,\mu)}-1}+1\right]$$

$$\langle a_+^\dagger(\mathbf{p})a_+(\mathbf{p})\rangle_{l.eq.} = \frac{R_T^2}{(2\pi)^3\omega_p}\int_{-\infty}^{+\infty} d\mu\frac{1}{e^{\beta\omega(p_T,\mu)}-1} = \frac{1}{(2\pi)^3\omega_p}\int_{\sigma^\mu} d\sigma u^\mu p_\mu\frac{1}{e^{\beta u^\mu p_\mu}-1}$$

$$(\mu = (m_T\tau)\sinh(\eta-\theta))$$

One-particle momentum spectra and vacuum terms:

$$\langle a_+^\dagger(\mathbf{p}) a_+(\mathbf{p})\rangle_{cond} = \frac{R_T^2}{(2\pi)^3\omega_p}\int_{-\infty}^{+\infty} d\mu |\beta(p_T,\mu,\tau)|^2 \left[\frac{2}{e^{\beta\omega(p_T,\mu)}-1}+1\right]$$

$$|\beta(p_T,\mu,\tau)|^2 = \frac{E-1}{2} \qquad \omega(p_T,\mu) = \sqrt{m_T^2+\frac{\mu^2}{\tau^2}}$$

$$E(p_T,\mu) = \frac{\pi\tau}{4\omega(p_T,\mu)} \times$$
$$\left[|\partial_\tau \widetilde{H}_{i\mu}^{(2)}(m_T\tau)|^2 + \omega^2(p_T,\mu)|\widetilde{H}_{i\mu}^{(2)}(m_T\tau)|^2\right]$$

WKB ansatz:

$$\widetilde{H}_{i\mu}^{(2)}(m_T\tau) = \exp(\pi\mu/2) H_{i\mu}^{(2)}(m_T\tau) =$$
$$e^{i\pi/4}\left[\frac{2}{\pi W(\tau,p_T,\mu)\tau}\right]^{1/2} \exp\left[-i\int_{\tau_0}^{\tau} d\tau' W(\tau',p_T,\mu)\right]$$

satisfies normalization condition

Adiabatic approximation: $\tau\omega(p_T,\mu) = \tau\sqrt{m_T^2 + \frac{\mu^2}{\tau^2}} \gg 1$

$\partial_\mu u^\mu = \frac{1}{\tau}$

Klein-Gordon equation:

$$\left(\partial_\tau^2 + \frac{1}{\tau}\partial_\tau + m_T^2 + \frac{\mu^2}{\tau^2}\right)\widetilde{H}_{i\mu}^{(2)}(m_T\tau) = 0$$

For the WKB ansatz: $W^2 = \omega^2 + \frac{1}{4\tau^2} - \frac{1}{2}\frac{\partial_\tau^2 W}{W} + \frac{3}{4}\left(\frac{\partial_\tau W}{W}\right)^2$

Can be solved by iteration, leading order in $(\tau\omega(p_T,\mu))^{-1}$

is $W^{(1)} = \omega$

For the WKB ansatz $|\beta|^2 = \frac{1}{4W\omega}\left[\left(\frac{1}{2}\frac{\partial_\tau W}{W} + \frac{1}{2\tau}\right)^2 + (W-\omega)^2\right]$

in the leading order is $|\beta^{(1)}|^2 = \frac{1}{16\omega^2\tau^2}$

Regularization is needed !

The local energy density of particles created from the "vacuum" diverges in the leading order of the adiabatic approximation :

$$\langle 0,\tau|u_\mu u_\nu T^{\mu\nu}(x)|0,\tau\rangle - \langle 0|u_\mu u_\nu T^{\mu\nu}(x)|0\rangle = \infty$$

because

$$\langle 0,\tau|a_+^\dagger(\mathbf{p}_1)a_+(\mathbf{p}_2)|0,\tau\rangle = \frac{R_T^2}{(2\pi)^3\sqrt{\omega_{p1}\omega_{p2}}}\int_{-\infty}^{+\infty} d\mu_1 e^{-i\mu_1(\theta_1-\theta_2)}|\beta(p_T,\mu,\tau)|^2$$

and $|\beta^{(1)}|^2 = \frac{1}{16\omega^2\tau^2}$

Physical picture: sudden decay of the quasiparticle vacuum at fixed $\tau = \sqrt{t^2 - z^2}$ means that all virtual particles become real ones .

Continuous decay : adiabatic regularization results in

$$|\beta|^2 \to |\beta|^{2(reg)} = |\beta|^2 - |\beta|^{2(A)}$$

$$\langle 0,\tau|u_\mu u_\nu T^{\mu\nu}(x)|0,\tau\rangle - \langle 0,\tau,A|u_\mu u_\nu T^{\mu\nu}(x)|0,\tau,A\rangle \neq \infty$$

One-particle momentum spectra and two-particle correlations without regularizations (but with some comments) in the leading order of the adiabatic approximation

One-particle momentum spectra :

$$\langle a_{+}^{\dagger}(\mathbf{p}) a_{+}(\mathbf{p})\rangle \approx n_{l.eq.}(p) + n_{cond}(p)$$

$$n_{l.eq.}(p) = \frac{R_T^2}{(2\pi)^3 \omega_p} \tau m_T \sqrt{\frac{2\pi}{\beta m_T}} \exp(-\beta m_T)$$

$$n_{cond}(p) = \frac{R_T^2}{(2\pi)^3 \omega_p} \frac{\pi}{16 m_T \tau}$$

Two-particle momentum spectra ：

$$\langle a_+^\dagger(\mathbf{p}_1)a_+^\dagger(\mathbf{p}_2)a_+(\mathbf{p}_1)a_+(\mathbf{p}_2)\rangle =$$
$$\langle a^\dagger(\mathbf{p}_1)a(\mathbf{p}_1)\rangle\langle a^\dagger(\mathbf{p}_2)a(\mathbf{p}_2)\rangle+\langle a^\dagger(\mathbf{p}_1)a(\mathbf{p}_2)\rangle\langle a^\dagger(\mathbf{p}_2)a(\mathbf{p}_1)\rangle$$

$$a^\dagger(\mathbf{p}_1)a(\mathbf{p}_2)\rangle = \langle a^\dagger(\mathbf{p}_1)a(\mathbf{p}_2)\rangle_{l.eq.}+\langle a^\dagger(\mathbf{p}_1)a(\mathbf{p}_2)\rangle_{cond}$$
$$\langle a^\dagger(\mathbf{p}_1)a(\mathbf{p}_2)\rangle_{l.eq.} \approx n_{l.eq.}(p)\,\mathrm{exp}\left(-\frac{R^2_{l.eq.}}{2}q_L^2\right),$$
$$\langle a^\dagger(\mathbf{p}_1)a(\mathbf{p}_2)\rangle_{cond} \approx n_{cond}(p)\,\mathrm{exp}\left(-\frac{R_{cond}}{2}|q_L|\right)$$

$$R_{cond} = \frac{2\tau}{\cosh\theta} \qquad R_{l.eq.} = \frac{\tau}{\sqrt{\beta m_T}\cosh\theta}$$

Two-particle correlation function

Fitted form of the correlation function :

$$C_{exp}(\mathbf{p},\mathbf{q}) = 1 + \lambda_{\mathbf{p}} F_{\mathbf{p}}(\mathbf{q})$$

$$\mathbf{p} = (\mathbf{p}_1 + \mathbf{p}_2)/2$$
$$\mathbf{q} = \mathbf{p}_2 - \mathbf{p}_1$$

$$F_{\mathbf{p}}(\mathbf{0}) = 1$$
$$F_{\mathbf{p}}(\mathbf{q}) \to 0$$
$$\text{for } |\mathbf{q}| \to \infty$$

Theoretical correlation function:

$$C(\mathbf{p},\mathbf{q}) = \frac{\langle a_+^\dagger(\mathbf{p}_1) a_+^\dagger(\mathbf{p}_2) a_+(\mathbf{p}_1) a_+(\mathbf{p}_2)\rangle}{\langle a_+^\dagger(\mathbf{p}_1) a_+(\mathbf{p}_1)\rangle \langle a_+^\dagger(\mathbf{p}_2) a_+(\mathbf{p}_2)\rangle} = 1 + \frac{\langle a^\dagger(\mathbf{p}_1) a(\mathbf{p}_2)\rangle \langle a^\dagger(\mathbf{p}_2) a(\mathbf{p}_1)\rangle}{\langle a^\dagger(\mathbf{p}_1) a(\mathbf{p}_1)\rangle \langle a^\dagger(\mathbf{p}_2) a(\mathbf{p}_2)\rangle}$$

$$C(\mathbf{p},0,0,q_L) \approx 1 + \left(\sqrt{\lambda_{l.eq.}} \exp\left(-\frac{R_{l.eq.}^2}{2} q_L^2\right) + \sqrt{\lambda_{cond}} \exp\left(-\frac{R_{cond}}{2}|q_L|\right)\right)^2$$

$$\lambda_{l.eq.} = \left(\frac{n_{l.eq.}}{n_{l.eq.} + n_{cond}}\right)^2, \quad n_{l.eq.}(p) = \frac{R_T^2}{(2\pi)^3 \omega_p} \tau m_T \sqrt{\frac{2\pi}{\beta m_T}} \exp(-\beta m_T)$$

$$\lambda_{cond} = \left(\frac{n_{cond}}{n_{l.eq.} + n_{cond}}\right)^2 \quad n_{cond}(p) = \frac{R_T^2}{(2\pi)^3 \omega_p} \frac{\pi}{16 m_T \tau}$$

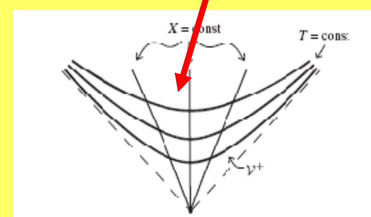
$$\sqrt{\lambda_{l.eq.}} + \sqrt{\lambda_{cond}} = 1 \qquad R_{cond} = \frac{2\tau}{\cosh\theta} \qquad R_{l.eq.} = \frac{\tau}{\sqrt{\beta m_T}\cosh\theta}$$

pp collisions at the LHC:

- There is some evidence that hydrodynamics can be successfully applied to describe flow-like features in high-multiplicity pp collisions.

  Therefore one can expect that quasi-equilibrium statistical operator can be utilized for reduced description of the system.

- High rate of (longitudinal) expansion in pp collisions $\tau = const$



$$\tau \simeq 1 \text{ fm/c} \qquad \partial_\mu u^\mu(x) = \frac{1}{\tau}$$

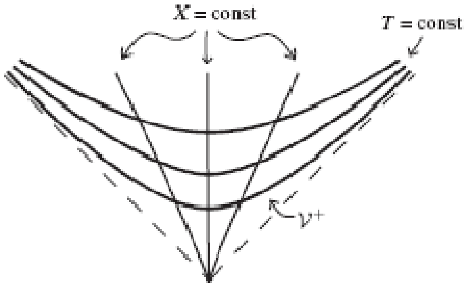
  can result in noticeable contributions to particle momentum spectra from quantum particle creation due to the ground-state decay

- Adiabatic approximation can be used for regularization

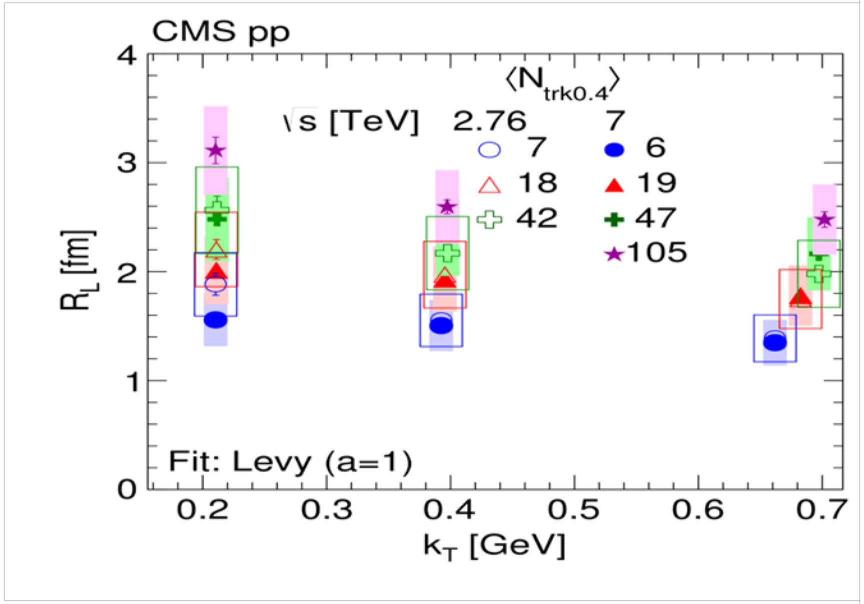
$$\tau\omega(p_T, \mu) = \tau\sqrt{m_T^2 + \frac{\mu^2}{\tau^2}} > 1$$

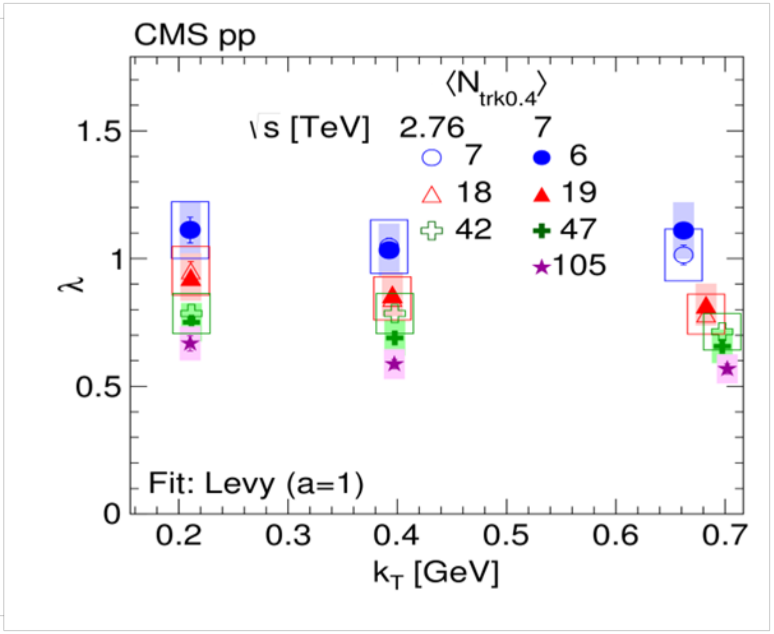
- There is no prolonged post-hydrodynamical kinetic stage of hadronic rescatterings: signals of the ground-state decay can be observed in particle momentum spectra and correlations.

Perhaps this effect has been already observed in pp collisions at the LHC: Suppression of the two-particle Bose-Einstein momentum correlation functions in high-multiplicity p + p collisions (CMS, ATLAS, ALICE)



CMS Collaboration:
Phys. Rev. C 97, 064912 (2018) (0.9-7 TeV);
arXiv:191008815 (13 TeV).





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Conclusions

- Matter produced in a high energy pp collision is locally restricted to the light cone with beginning at t = z = 0 plane of the Minkowski spacetime manifold and initial conditions for expanding quantum fields are defined not at

  $t_{in} = const$ but at $\tau_{in} = \sqrt{t^2 - z^2} = const$

- Hydrodynamics can describe particle momentum spectra in AA/pp collisions. Therefore there is possibility of the reduced description of the system by means of the corresponding quasi equilibrium statistical operator whose lowest energy eigenstate does not coincide with the Minkowski vacuum. Particle creation from this “quasiparticle vacuum” has an analogue with the cosmological particle creation [see, e.g., N.D. Birrell, P.C.W. Davies, Quantum Fields in Curved Space].

- The physical picture is that particles are produced by the emitter with two different scales approximately attributed to the expanding ideal gas in local equilibrium state and to the highly entangled state (condensate) of correlated pairs of particles. Signals of particle production from this condensate can be noticeable if rate of matter expansion is high, and if effect of rescatterings for produced particles is small .

Conclusions

- Perhaps, signals of quantum particle creation from quasi equilibrium ground state condensate have been already observed in measured two-pion momentum correlations in pp collisions at the LHC (ALICE, ATLAS, CMS Collaborations). Specifically, **apparent** suppression of the measured Bose-Einstein momentum correlations of two identical charged pions can take place due to the two-scale mechanism of particle emission and different momentum dependence of the corresponding particle emission regions.

- Realistic generalization of the model is needed to make possible quantitative comparison with experimental data.

- My talk is based on

1) S.V. Akkelin, Eur. Phys. J. A (2019) **55**: 78.

2) S.V. Akkelin, in preparation.

Thank you !