Nonequilibrium meson production in strong fields.

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Colloqium on Nonequilibrium phenomena in strongly correlated systems,
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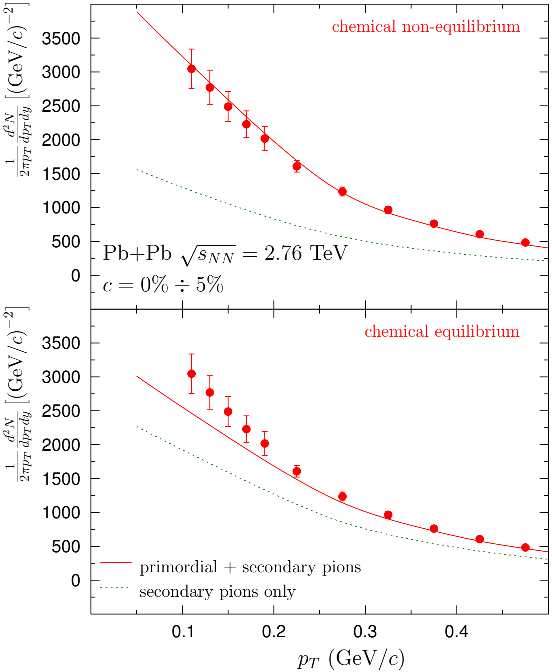


V.Begun, arXiv:1512.09157

Schwinger effect and thermalization

Using this analogy that $|eE| = \sigma$ with $\sigma \sim 0.19$ GeV^2 being the string tension, the transverse spectrum of particles according to the Schwinger mechanism is

$$\frac{dN_{\rm Schwinger}}{d^2p_\perp} \sim \exp\left(-\frac{\pi\varepsilon_\perp^2}{\sigma}\right) \ ,$$

$$\varepsilon_\perp = \sqrt{m^2 + p_\perp^2} \ .$$

This spectrum of is nonthermal and thus contradict the observation of thermal spectra in HIC

$$\frac{dN_{\rm exp}}{d^2p_\perp} \sim \exp\left(-\frac{\varepsilon_\perp}{T_{\rm eff}}\right) \ , \ \ T_{\rm eff} \sim 180$$

Thermal spectra in HIC

Is there enough time for the thermal equilibration of the system by collisions ?

Alternative picture for the emergence of a thermal spectrum : Hawking-Unruh radiation

$$T_H = \sqrt{\frac{\sigma}{2\pi}} \sim 173\ \mathrm{MeV}.$$

Synthesis of both pictures

If the string tension in the Schwinger process for flux tube decay would fluctuate and follow, e.g., a Poissonian-like distribution

$$P(\sigma) = \exp(-\sigma/\sigma_0)/\sqrt{\pi\sigma\sigma_0}\ ,$$

$$\int d\sigma P(\sigma) = 1$$

$$\langle\sigma\rangle = \int d\sigma\sigma P(\sigma) = \sigma_0/2$$

Blaschke, D. B. and Smolyansky, S. A. and Panferov, A. and Juchnowski, L.
Particle Production in Strong Time-dependent Fields
doi: 10.3204/DESY-PROC-2016-04/Blaschke

Synthesis of both pictures

after averaging with the string tension fluctuations becomes exponential, i.e. thermal with the temperature parameter $T = \sqrt{\langle\sigma\rangle/(2\pi)}$,

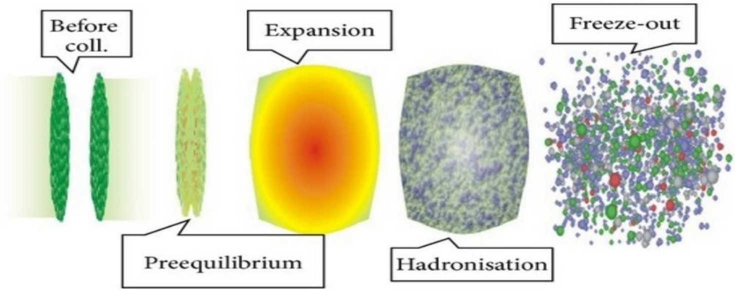
$$\int d\sigma P(\sigma) \exp\left(-\frac{\pi\varepsilon_\perp^2}{\sigma}\right) = \exp\left(-\frac{\varepsilon_\perp}{T}\right) \ .$$

doi: 10.3204/DESY-PROC-2016-04/Blaschke

Chiral symmetry restoration in hadronic phase K^+/π^+

$$\frac{P(s\bar{s})}{P(u\bar{u})} = \frac{P(s\bar{s})}{P(d\bar{d})} = \gamma_s = \exp\left(-\pi \frac{m_s^2 - m_q^2}{2\sigma}\right),$$

Cassing, Palmese, Moreau, Bratkovskaya PRC 93 014902


Before coll.
Expansion
Freeze-out
Preequilibrium
Hadronisation

Time dependent mass and dispersion relation

- Dispersion relation for σ and π

$$\omega_\sigma(t,\vec{p}) = \sqrt{m_\sigma(T(t))^2 + \vec{p}^2}\ , \quad \omega_\pi(\vec{p}) = \sqrt{m_\pi^2 + \vec{p}^2}\ ,$$

- The mass evolution of σ is governed by

$$m_\sigma(T(t)) = [m_\sigma(0) - m_\pi]\sqrt{1 - \frac{T(t)}{T_c}} + m_\pi\ , \quad T(t) = \frac{T_0\ t_0}{t}\ , \quad t \geq t_0\ ,$$

- Temperature is given by

$$T(t) = \frac{T_0\ t_0}{t}\ , \quad t \geq t_0\ ,$$

$$T(t) \leq T_c$$

Kinetic equation for π

$$\frac{\partial f_\pi}{\partial t}(t,\vec{p_1}) - \frac{\dot{R}(t)}{R(t)} \cdot \vec{p_1} \frac{\partial f_\pi}{\partial \vec{p_1}} =$$

$$(1+f_\pi(t,\vec{p_1}))\left(\int d^3p_\sigma \frac{d^3p_2}{(2\pi)^3 4w_\sigma w_2} \Gamma_{\sigma\to\pi\pi}(\vec{p}_\sigma,\vec{p_1},\vec{p_2})\,(1+f_\pi(t,\vec{p_2}))\,f_\sigma(t,\vec{p}_\sigma)\right)$$

$$-f_\pi(t,\vec{p_1})\left(\int d^3p_\sigma \frac{d^3p_2}{(2\pi)^3 4w_\sigma w_2} \Gamma_{\pi\pi\to\sigma}(\vec{p}_\sigma,\vec{p_1},\vec{p_2}) f_\pi(t,\vec{p_2})\,(1+f_\sigma(t,\vec{p}_\sigma))\right)$$

$R(t) = v_R \cdot t$ is radius of expanding fireball

J. Bernstein *Kinetic theory in the expanding universe* Cambridge Press 1988

Ł.Juchnowski, D.B.Blaschke, T.Fischer, S. A. Smolyansky, J.Phys.Conf.Ser. 673 (2016) 1, 012009

Kinetic equation for σ

$$\frac{\partial f_\sigma}{\partial t}(t,\vec{p}_\sigma) - \frac{\dot{R}(t)}{R(t)} \cdot \vec{p}_\sigma \frac{\partial f_\sigma}{\partial \vec{p}_\sigma} =$$

$$= \frac{\Delta_\sigma(t,\vec{p}_\sigma)}{2} \int_{t_0}^{t} dt' \Delta_\sigma(t',\vec{p}_\sigma)\left(1 + f_\sigma(t',\vec{x},\vec{p}_\sigma)\right)\cos\left(2\theta_\sigma(t,t',\vec{p}_\sigma)\right)$$

$$+ \left(1 + f_\sigma(t,\vec{p}_\sigma)\right)\left(\int d^3p_1 \frac{d^3p_2}{(2\pi)^6 4w_1w_2} \Gamma_{\pi\pi\to\sigma}(\vec{p}_\sigma,\vec{p}_1,\vec{p}_2) f_\pi(t,\vec{p}_1) f_\pi(t,\vec{p}_2)\right)$$

$$- f_\sigma(t,\vec{p}_\sigma)\left(\int d^3p_1 \frac{d^3p_2}{(2\pi)^6 4w_1w_2} \Gamma_{\sigma\to\pi\pi}(\vec{p}_\sigma,\vec{p}_1,\vec{p}_2)\left(1 + f_\pi(t,\vec{p}_1)\right)\left(1 + f_\pi(t,\vec{p}_2)\right)\right)$$

The vacuum transition amplitude and dynamical phase

$$\Delta_\sigma(t,\vec{p}_\sigma) = \frac{m_\sigma}{w_\sigma^2}\frac{\partial m_\sigma}{\partial t}, \qquad \theta_\sigma(t,t',\vec{p}_\sigma) = \int_{t'}^{t} dt'' w_\sigma(t'',\vec{p}_\sigma)$$

A.V Filatov, *et al.* , Phys. Part. Nucl. **39** 1116 (2008)

Schmidt, Blaschke *et al.* Int.J.Mod.Phys. E7 (1998) 709-722

Reaction rate

For the σ decay and regeneration we assume a constant matrix element $|M|^2 = \mathrm{const}$ so that the momentum dependence of $\Gamma_{\sigma\to\pi\pi}$ is simply given by the momentum conserving delta-function

$$\begin{aligned}\Gamma_{\sigma\to\pi\pi}(\vec{p}_\sigma, \vec{p}_1, \vec{p}_2) &= (2\pi)^4\delta^4(p_\sigma - p_1 - p_2)|M|^2 \\ &\to (2\pi)^4\delta(w_\sigma - w_1 - w_2)\delta^3(\vec{p}_\sigma - \vec{p}_1 - \vec{p}_2)\ .\end{aligned}$$

Elastic scattering

$$\frac{df_\pi(\varepsilon_1)}{dt} = \frac{|M_{fi}|^2}{64\pi^3\varepsilon_1}\int\int F(f)\frac{D}{p_1}d\varepsilon_1' d\varepsilon_2',$$

$$F(f) = [1+f_1]\,[1+f_2]f_1'f_2' - [1+f_1']\,[1+f_2']f_1 f_2 \ ,$$

$$D \equiv \min[p_1, p_2, p_1', p_2']$$

Semikoz, Tkachev, Phys. Rev. D 55, 489

Thermal initial conditions (LHC)

$$f_i(t_0, \vec{p}) = g_i \left[\exp(\sqrt{p^2 + m_i^2(T_0)}/T_0) - 1 \right]^{-1} , \quad i = \pi, \sigma \ .$$

$$T_0 = Tc = 170 \text{ MeV}$$

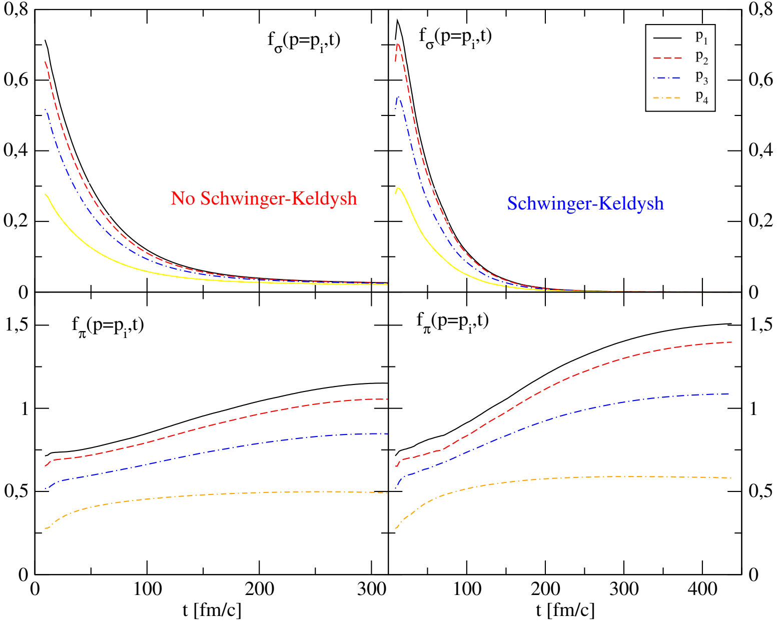
$$\mu = 0$$

$$t_0 = 9 \text{ fm/c}$$

$$m_\pi = 140 \text{ MeV}$$

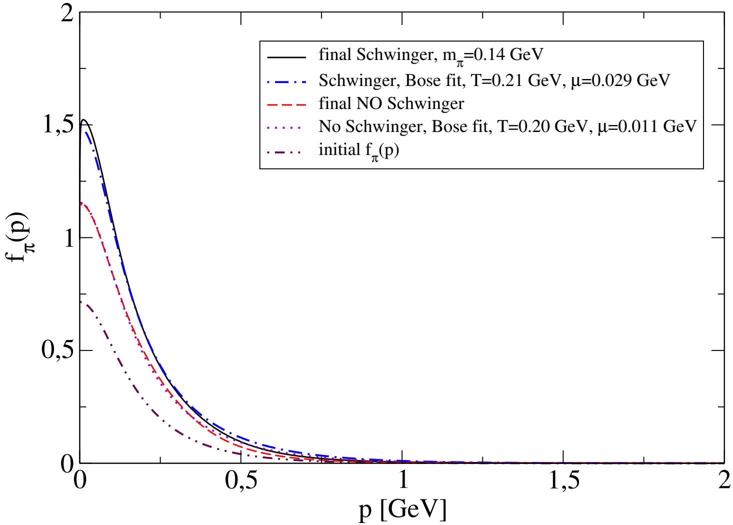
$$m_\sigma(0) = 550 \text{ MeV}$$

Value of t_0 corresponding to a Hubble flow velocity of $v_R = 0.72$ c for gold nuclei with radius $R_0 = 6.5$ fm

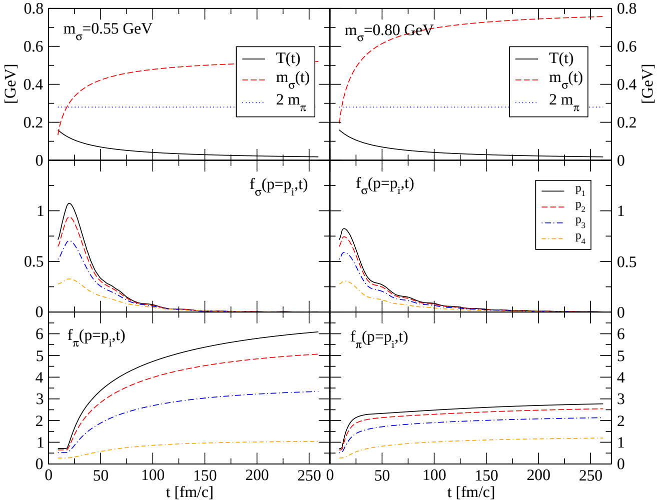


$p_1 = 5$ MeV, $p_2 = 50$ MeV, $p_3 = 100$ MeV, $p_4 = 200$ MeV

Pion distribution function

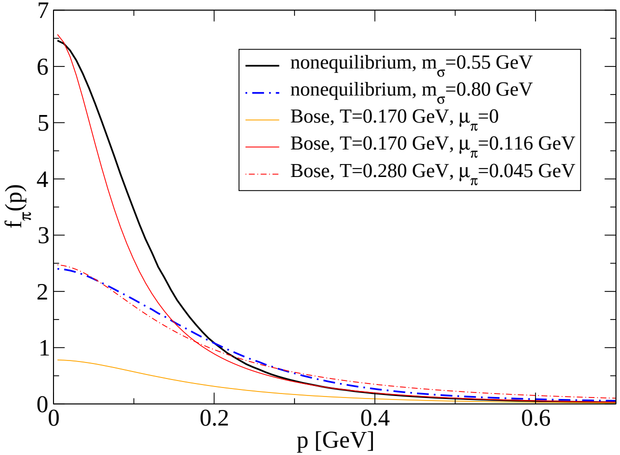


$$r_+ = \frac{n_{\text{final}}}{n_{\text{initial}}} = 2.57 \qquad r_- = 2.08$$



$$p_1 = 5 \text{ MeV}, \; p_2 = 50 \text{ MeV}, \; p_3 = 100 \text{ MeV}, \; p_4 = 200 \text{ MeV}$$

Pion distribution function (no expansion term)



$$r_+ = \frac{n_{\text{final}}}{n_{\text{initial}}} = 3.18 \qquad r_- = 2.98$$

Summary

- Expansion term

$$\frac{\dot{R}}{R}\mathbf{p}\cdot\frac{\partial f_i}{\partial \mathbf{p}}$$

and time dependent dispersion relation

$$\omega_\sigma(t,\vec{p}) = \sqrt{m_\sigma(T(t))^2 + \vec{p}^2}$$

seems to be main driving "force"

- Production ratio is not high ⇒ enhancment in partonic phase (?)
- More chiral physics is needed
- There is a need to study B-E condensation

$$\tilde{f} = f(\vec{\mathbf{p}},t) + (2\pi)^3 N_c(t)\delta^3(\vec{\mathbf{p}})$$

- Inclusion of inelastic scattering

THE END

The resulting system of kinetic equations to be solved is given by

$$\frac{\partial f_\sigma}{\partial t}(t, p_\sigma) = \frac{\Delta_\sigma(t, p_\sigma)}{2} \int_{t_0}^{t} dt' \Delta_\sigma(t', p_\sigma) \left(1 + f_\sigma(t', p_\sigma)\right) \cos\left(2\theta_\sigma(t, t', p_\sigma)\right.$$

$$- \frac{1}{8\pi} f_\sigma(t, p_\sigma) \frac{1}{p_\sigma w_\sigma} \int_{p_1^-}^{p_1^+} p_1 dp_1 \frac{|M|^2}{w_1} \left(1 + f_\pi(t, p_1)\right) \left(1 + f_\pi(t, p_2\right.$$

$$\frac{\partial f_\pi}{\partial t}(t, p_1) = \frac{1}{8\pi} \left(1 + f_\pi(t, p_1)\right) \frac{1}{p_1 w_1} \int_{p_\sigma^-}^{p_\sigma^+} p_\sigma dp_\sigma \frac{|M|^2}{w_\sigma} f_\sigma(t, p_\sigma) \left(1 + f_\pi(t, p_2\right.$$

where

$$p_1^\pm = \frac{1}{2} \left| p_\sigma \pm w_\sigma \sqrt{1 - \frac{4m_\pi^2}{m_\sigma^2}} \right|, \qquad p_\sigma^\pm = \frac{m_\sigma^2}{m_\pi^2} \frac{1}{2} \left| p_1 \pm w_1 \sqrt{1 - \frac{4m_\pi^2}{m_\sigma^2}} \right| \quad (3)$$