Thermalisation properties of various field theories

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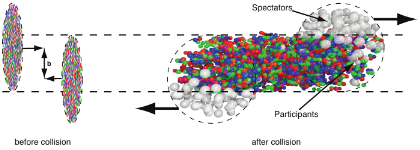
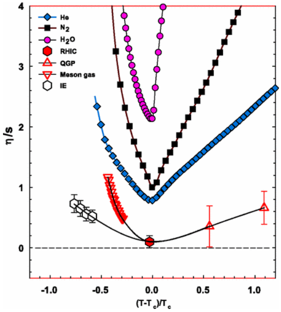
Viscosity of hadronic matter





[R.Lacey et al. (2007), PhysRevLett.98.092301]

- observation: nearly ideal liquid
- relevant quantity: η/s (damping of hydrodynamic waves)

Introduction

- viscosity (η) in classical field theory
- small transport coefficient $\Leftrightarrow$ strongly interacting system $\rightarrow$ non-perturbative
- Boltzmann equation, MC (less sensitive for $\omega \rightarrow 0$)
- different approach:
- test: classical Φ^4 theory

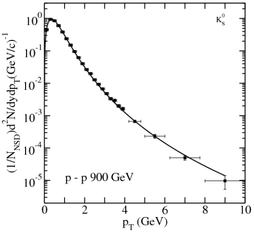
$$\mathcal{H} = \frac{1}{2}\Pi^2 + \frac{1}{2}(\nabla\Phi)^2 + \frac{m^2}{2}\Phi^2 + \frac{\lambda}{24}\Phi^4 \qquad (1)$$

- "toy model" which may show interesting effects mentioned above
- Homor, M. M. and Jakovac, A., *Shear viscosity of the Φ^4 theory from classical simulation*, PhysRevD.92.105011, 2015

Tsallis distribution in p-p collisions and hadronization

Urmossy, K. and Barnaföldi, G.G. and Harangozó, Sz. and Biró, T.S. and Xu, Z.,
A 'soft + hard' model for heavy-ion collisions, arXiv:1501.02352 [hep-ph], 2015

Cleymans, J. and Worku, D.,
The Tsallis Distribution in Proton-Proton Collisions at $\sqrt{s}$ = 0.9 TeV at the LHC,
J.Phys.G39:025006, 2012



Khachatryan, Vardan and others, *Transverse-momentum and pseudorapidity distributions of charged hadrons in pp collisions at $\sqrt{s} = 7$ TeV*,
CMS Collaboration, Phys.Rev.Lett. 105.022002, 2010

Aamodt, K. and others,
Production of pions, kaons and protons in pp collisions at $\sqrt{s} = 900$ GeV with ALICE at the LHC, Eur.Phys.J.C71:1655, 2011

Simulation

- canonical equations, periodic boundary conditions, leap-frog algorithm
- initial conditions: $\left\{\Pi\left(t_0+\frac{\delta t}{2}\right),\Phi(t_0)\right\}$
- uniform random for Π
- Canonical eq. of $\dot{\Phi}$ (1st part of time step): Initial condition $\rightarrow \Phi(t_0+\delta t)$
- Canonical eq. of $\dot{\Pi}$ (2nd part of time step): $\left\{\Phi(t_0+\delta t),\Pi\left(t_0+\frac{\delta t}{2}\right)\right\} \rightarrow \Pi\left(t_0+\frac{3\delta t}{2}\right)$
- input parameters: N^3 lattice size, $a=1$ (grid), λ (interaction), m^2 Lagrangian-mass

Total energy

$$E = \sum_{\mathbf{i} \in U} \frac{1}{2}\Pi_{\mathbf{i}}^2 + \frac{1}{2}(\nabla\Phi)_{\mathbf{i}}^2 + \frac{m^2}{2}\Phi_{\mathbf{i}}^2 + \frac{\lambda}{24}\Phi_{\mathbf{i}}^4, \qquad (2)$$

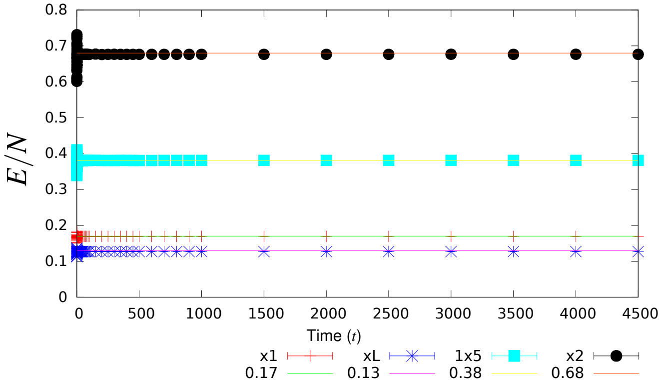


Figure: Time dependence of E/N where $N = 50^3$

Temperature $\langle|\Pi_k|^2\rangle = 2N^3T$

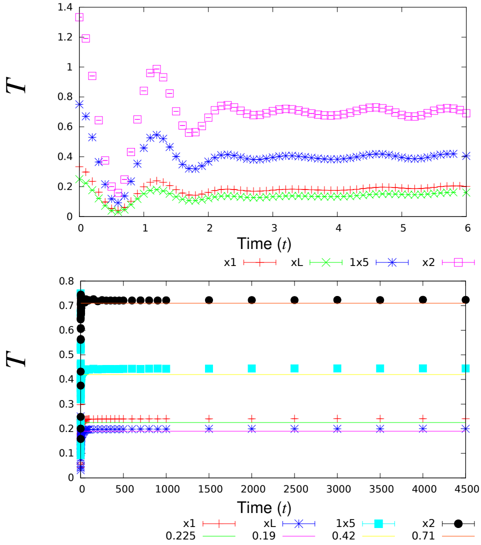


Figure: Time dependence of temperature

Expectation values of local quantities

- Local quantity: $A(\Phi, \Pi)$
- Real measurement is the time average:

$$\langle A(\Phi, \Pi) \rangle = \frac{1}{t} \int_{t_0}^{t_0+t} \mathrm{d}t' A(\Phi(t), \Pi(t)) \qquad (3)$$

- Inserting δ integral $\langle A(\Phi, \Pi) \rangle =$

$$\int \mathcal{D}\bar{\Phi}\mathcal{D}\bar{\Pi} A(\bar{\Phi}, \bar{\Pi}) \frac{1}{t} \int_{t_0}^{t_0+t} \mathrm{d}t' \delta(\bar{\Phi} - \Phi(t)) \delta(\bar{\Pi} - \Pi(t)) \qquad (4)$$

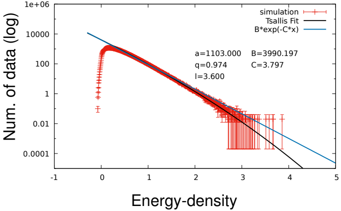
- the second part is a histogram $f(\bar{\Phi}, \bar{\Pi})$
- Time-average $\rightarrow$ Ensemble average

$$\langle A(\Phi, \Pi) \rangle = \int \mathcal{D}\bar{\Phi}\mathcal{D}\bar{\Pi} A(\bar{\Phi}, \bar{\Pi}) f(\bar{\Phi}, \bar{\Pi}) \qquad (5)$$

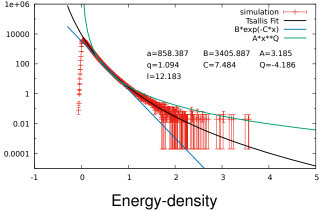
- e.g. canonical: $e^{-\beta\mathcal{H}}$

Energy histogram

Early time energy-distribution function is not Boltzmannian



(a) uniform init.



(b) sech init.

Various fits on logscale energy histogram

Tsallis distribution is an excellent fit!

$$f(x) = a\left[1 + (q-1)\beta x\right]^{\frac{1}{1-q}} \quad (6)$$

$\rightarrow$ consider the time evolution of q

Not Tsallis?

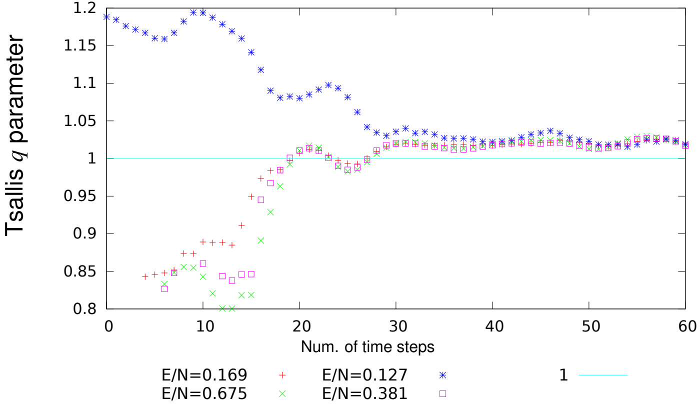


Figure: Time dependence of the Tsallis parameter

Tsallis?

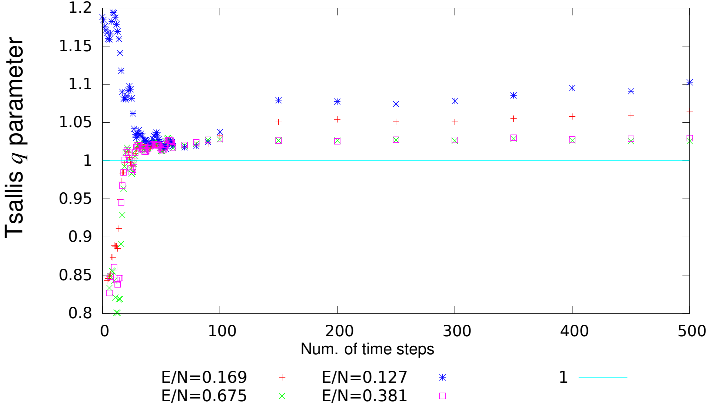


Figure: Time dependence of the Tsallis parameter

Just pre-thermal?

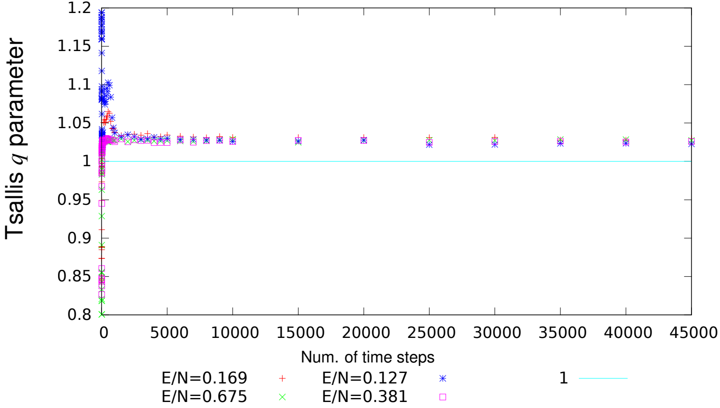


Figure: Time dependence of the Tsallis parameter

$$q \approx 1.026$$

$\Pi(x)$ histogram

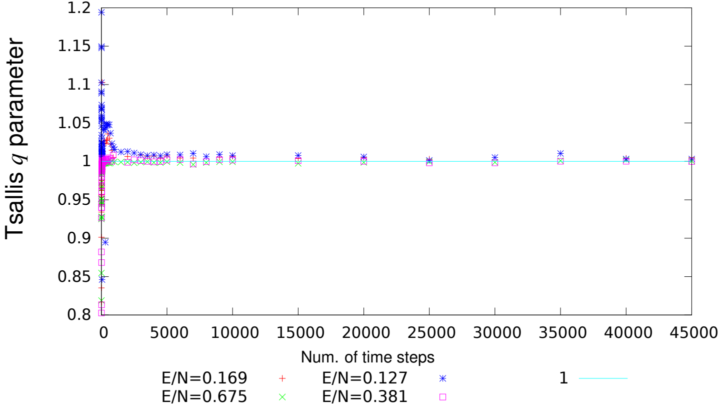
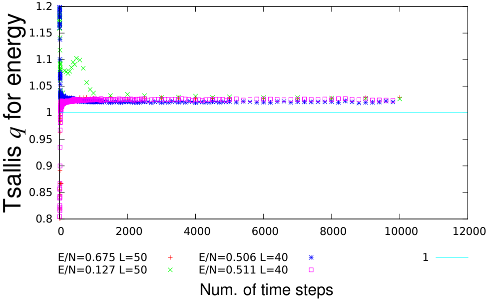
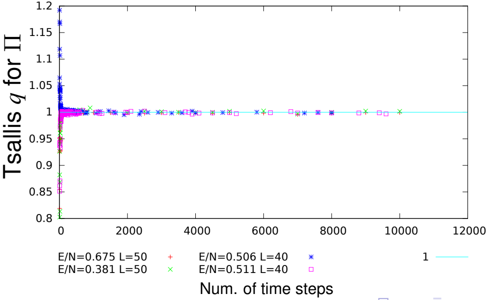


Figure: Time dependence of the Tsallis parameter for Π histogram

$$q \approx 0.999$$

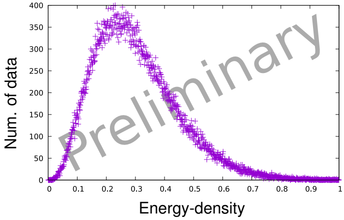
Lattice size

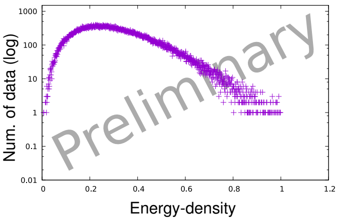




Future plans

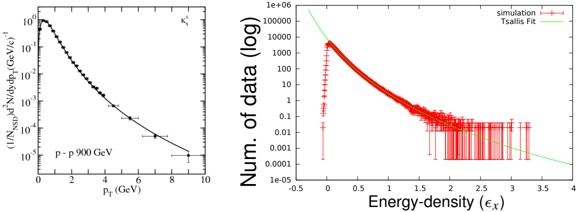
- SU(3) Yang-Mills MC with heatbath
- $N_t = 20$, $Ns = 10$ and $\beta = 7.5$





SU(3) Yang - Mills - preliminary!

Interpretation



Experiment vs. Φ^4 simulation

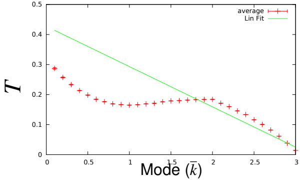
Suggestions:

- hadrons are created locally
- creation probability depends on local energy density
- local energy density distribution can be determined by computer simulations $\rightarrow$
- it might be a tool for measuring hadron distribution function

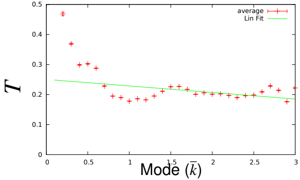
Thank you for your attention!

Equipartition

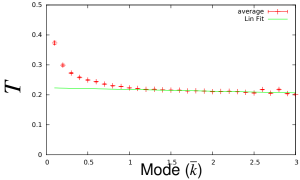
equilibrium → equipartition



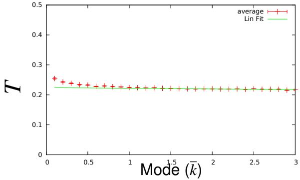
(e) $t = 2$



(f) $t = 8$



(g) $t = 200.1$



(h) $t = 4500.1$

Figure: Equipartition during time evolution ($\lambda = 5$)