The

Thermodynamics

of a geometrically confined

small system

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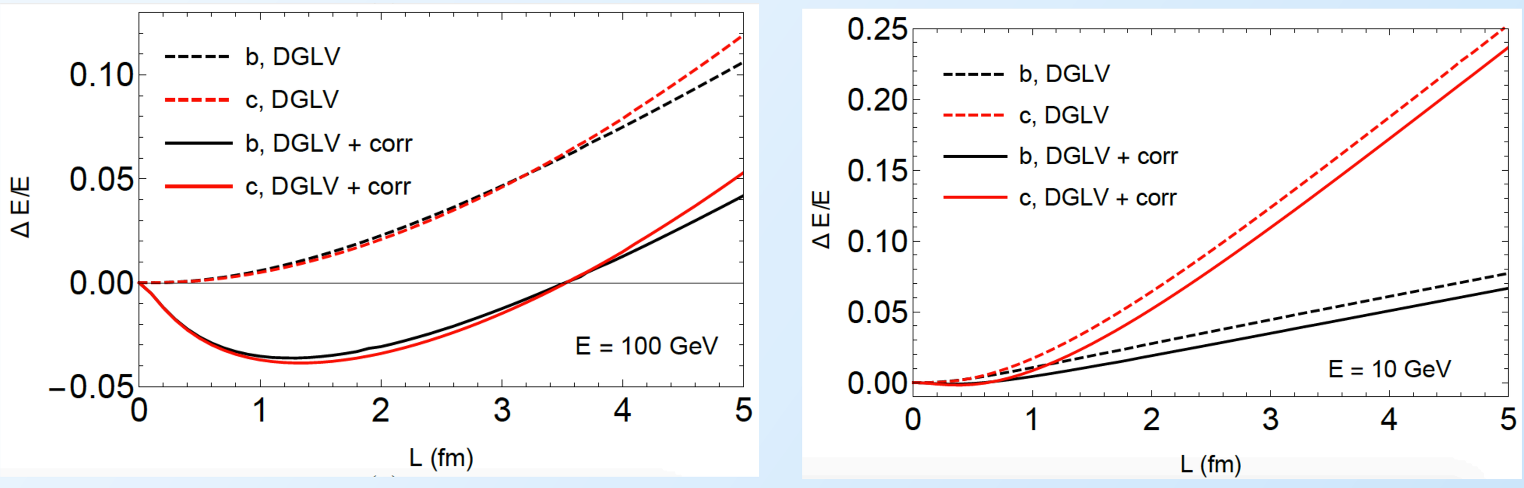
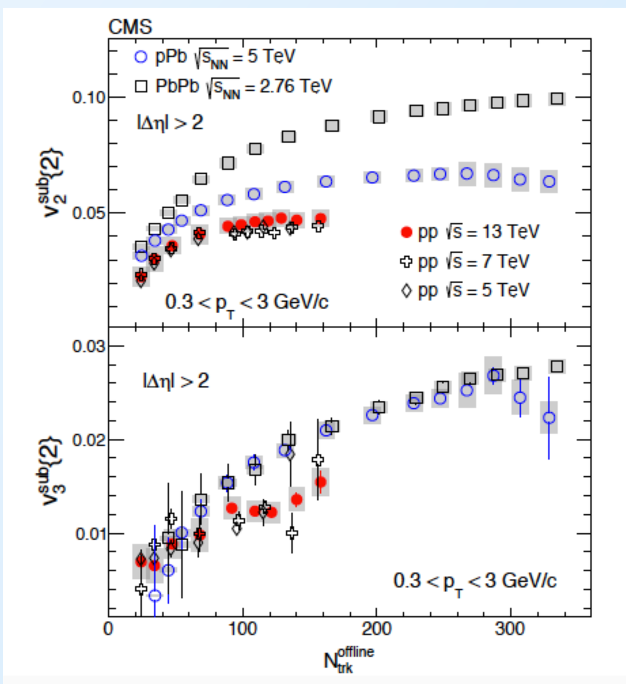
Abstract

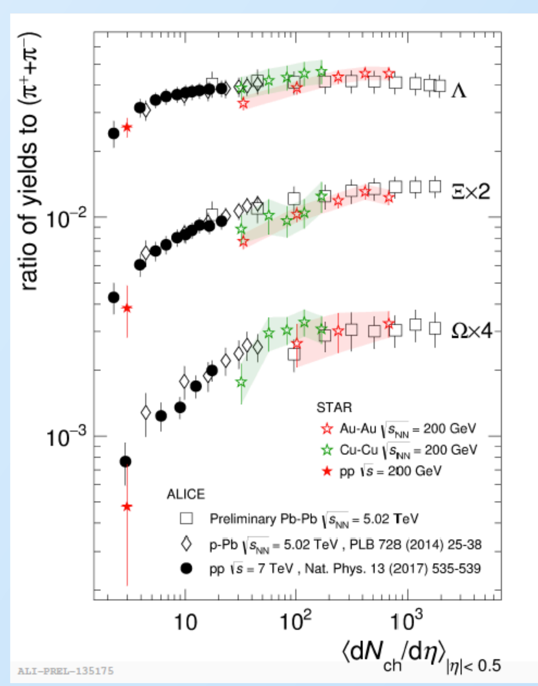
The emergence of evidence for collectivity and strangeness enhancement in small colliding systems has raised urgent questions surrounding the apparent absence of energy loss among the observables that are traditionally attributed to the presence of a Quark Gluon Plasma in heavy ion collisions. However, theoretical difficulties abound in the calculation of any measure of the energy loss, resulting in methods that were highly successful in the heavy ion regime coming up empty handed in the small system arena. We present a novel approach, generalizing standard thermal field theory and thermodynamic techniques, to probe the thermodynamic behavior of a small system. We consider first a single free scalar field theory that is geometrically confined. We investigate the partition function along with the usual thermodynamic quantities, as well as the thermodynamic stability and statistical fluctuations of such a system. Our results, while still approaching the Stefan-Boltzmann limit for large systems, offer new insights into the thermodynamics of smaller systems and exhibit new, Casimir-like effects, thereby also providing a natural solution to the so-called infra-red Linde problem.



IK [3]



ALICE: Strangeness enhancement [1]



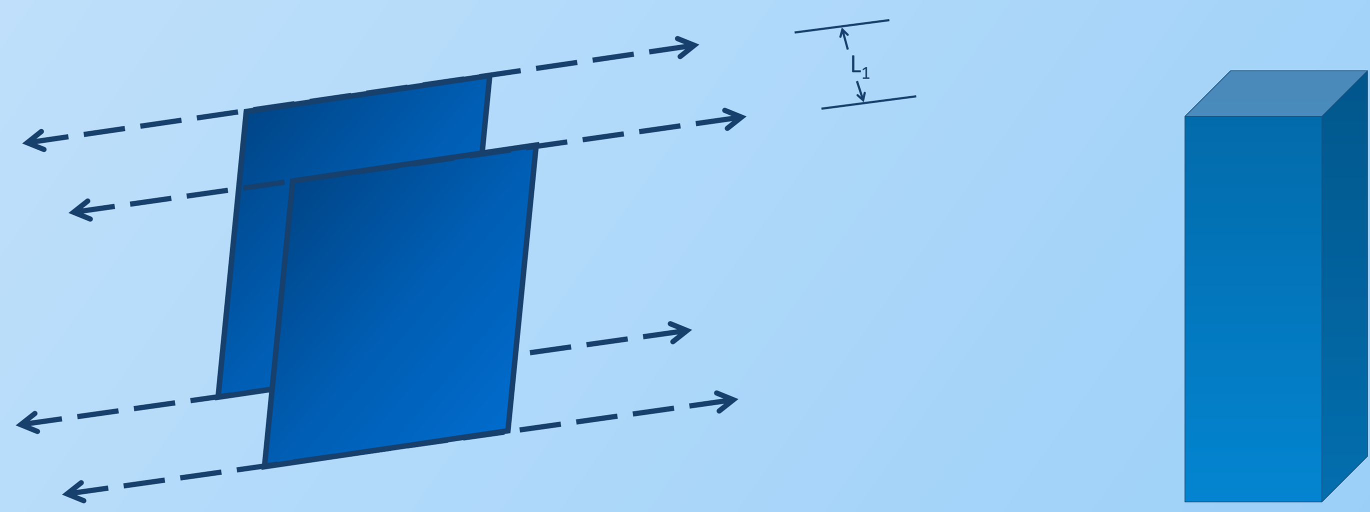
CMS: Collectivity in pp [2]

Motivation

The last two Quark Matter conferences have sported well attended and vigorously debated small system tracks. A number of traditional QGP signatures have been observed in small colliding systems, with the notable exception of significant energy loss, demanding a better understanding of the underlying physics.

The theoretical difficulties surrounding applying the pQCD methods that have been so successful in describing energy loss in heavy ion collisions (DGLV, AMY, ASW, etc) have been highlighted in the past [3]. In an attempt to more fully understand the finite size effects on crucial parameters that enter into pQCD calculations (such as the Debye screening length), we investigate the thermodynamics of small systems.

In a first attempt at describing a deconfined field of gluons, we have considered a single, free, massless scalar field and confined it geometrically.



Setup

We compute the partition function for a scalar field theory confined between two infinite parallel planes (the extension to an infinite tube of fully compactified box is straightforward) with Dirichlet boundary conditions. The usual thermal field theoretic methods [4,5] lead to

$$\ln \mathcal{Z}^{(1)} = -\sum_{n\in}\sum_{\ell_1\in}\sum_{n_k\in^{D-2}} \ln\left[\beta^2\left(\omega_n^2+\omega_{\ell_1}^2+\omega_k^2+m^2\right)\right]$$

From which one may obtain an expression for the free energy:

$$f(T,\,\{L_i\}) \equiv -\frac{T}{V}\ln \mathcal{Z}(T,\,\{L_i\}).$$

Using a combination of Epstein-Zeta and dimensional regularization, one obtains, for the case of one compactified dimension

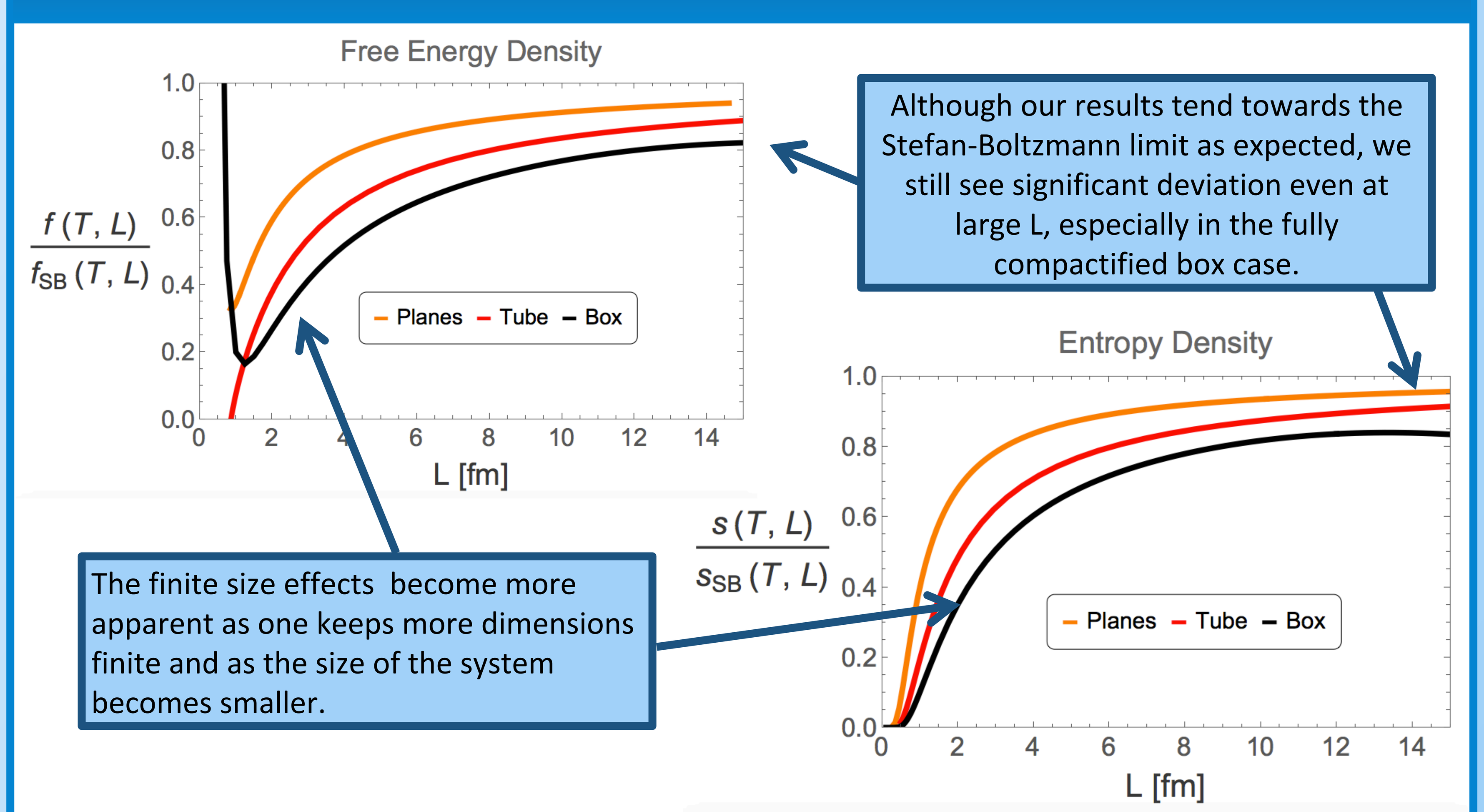
$$f^{(1)} = -\frac{\pi^2}{1440L_1^4}-\frac{T^2}{2L_1^2}\sum_{\ell=1}^{\infty}\left[\ell\,\mathrm{Li}_2\left(\exp^{-\frac{\pi\ell}{TL_1}}\right)\right]-\frac{T^3}{2\pi L_1}\sum_{\ell=1}^{\infty}\left[\mathrm{Li}_3\left(\exp^{-\frac{\pi\ell}{TL_1}}\right)\right].$$

Main analytic result

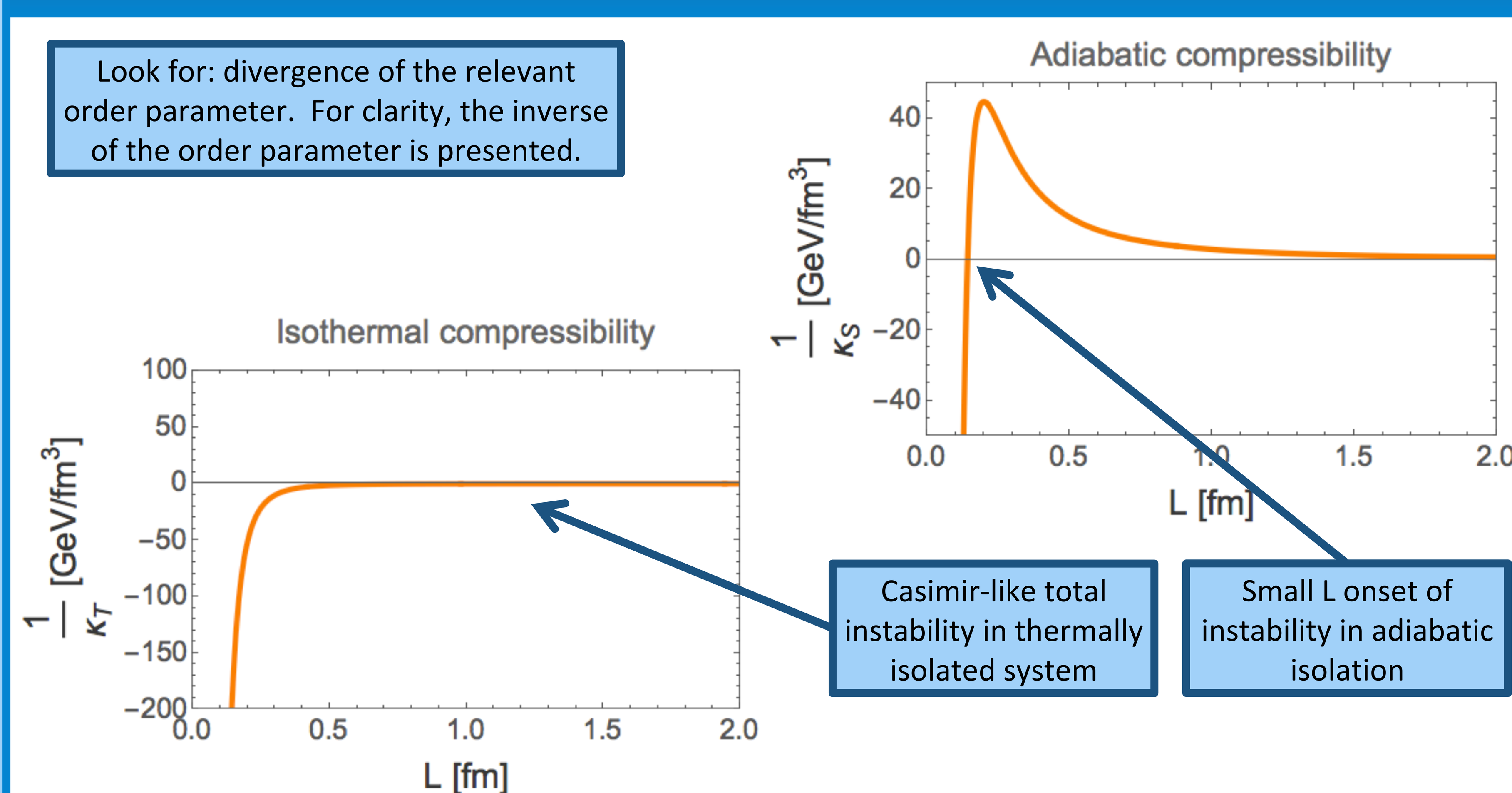
$$f^{(c)} = \frac{\Gamma\left(-\frac{D-c}{2}\right)\left(\frac{\bar{\Lambda}^2e^{\gamma_E}}{4\pi}\right)^{2-\frac{D}{2}}}{2(4\pi)^{\frac{D-1}{2}}\prod_{i=1}^{c}(L_i)\Gamma\left(-\frac{1}{2}\right)}E_c^0\left(-\frac{D-c}{2};\left(\frac{\pi}{L_1}\right)^2,\ldots,\left(\frac{\pi}{L_c}\right)^2\right)$$
$$-\frac{2\,T^{D-c}\left(\frac{\bar{\Lambda}^2e^{\gamma_E}}{4\pi}\right)^{2-\frac{D}{2}}}{(2\pi)^{\frac{D-1}{2}}\prod_{i=1}^{c}(L_i)}\sum_{s=1}^{\infty}\sum_{\boldsymbol{\ell}\in\mathbb{N}^c}\left[\left(\frac{\sum_{i=1}^{c}\left(\frac{\pi\ell_i}{L_i}\right)^2}{(sT)^2}\right)^{\frac{D-1}{4}}K_{\frac{D-c}{2}}\left(\frac{s}{T}\sqrt{\sum_{i=1}^{c}\left(\frac{\pi\ell_i}{L_i}\right)^2}\right)\right]$$

Results

Small system deviations



2nd order phase transition



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