Dynamics of critical fluctuations in heavy-ion collisions

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and the grant “Étoiles montantes en pays de la Loire”

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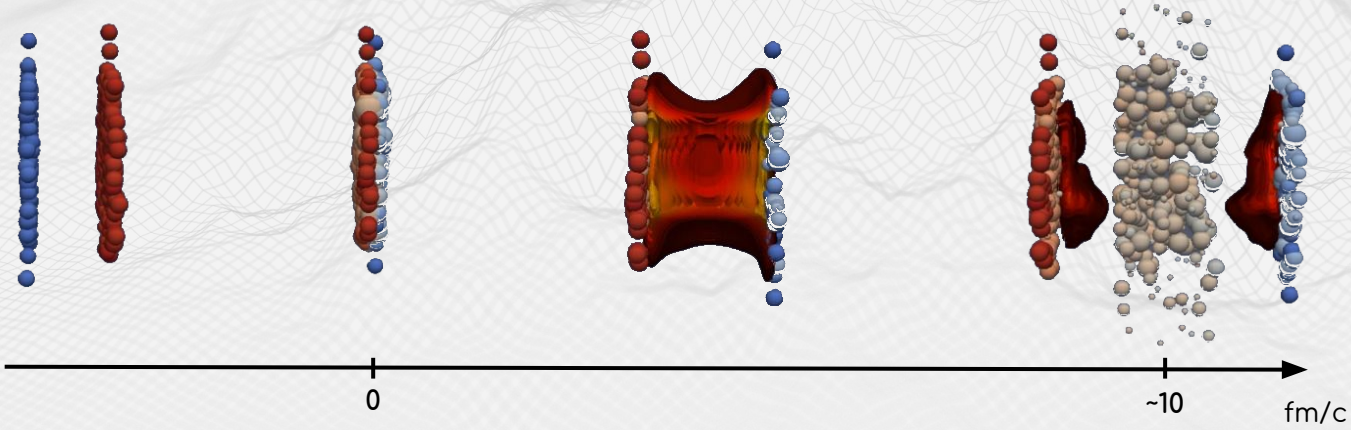
Introduction

Deconfined state of strongly interacting matter : The quark-gluon plasma.

Experimentally studied in heavy-ion collision.



MADAI collaboration, Hannah Petersen and Jonah Bernhard

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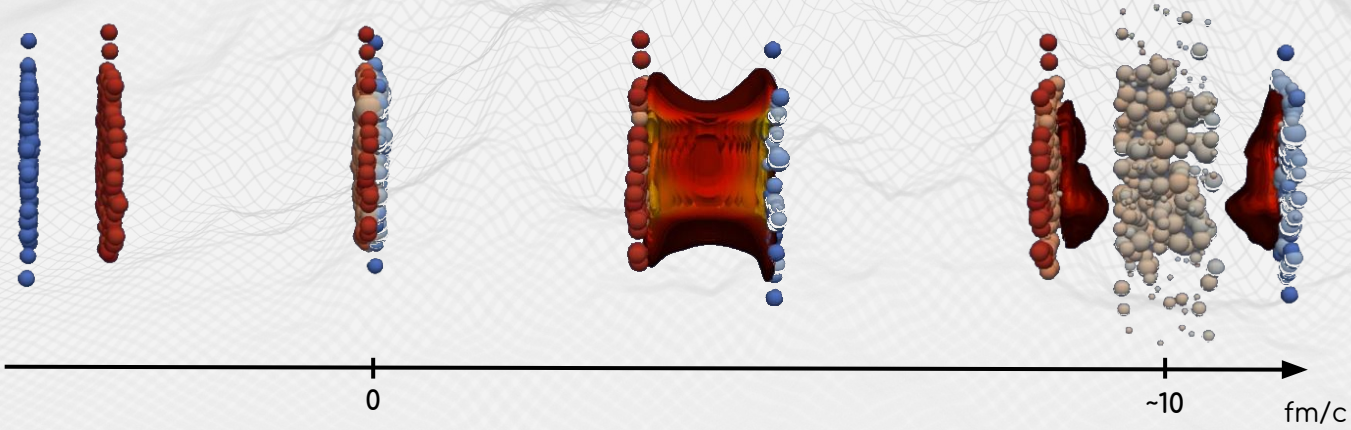
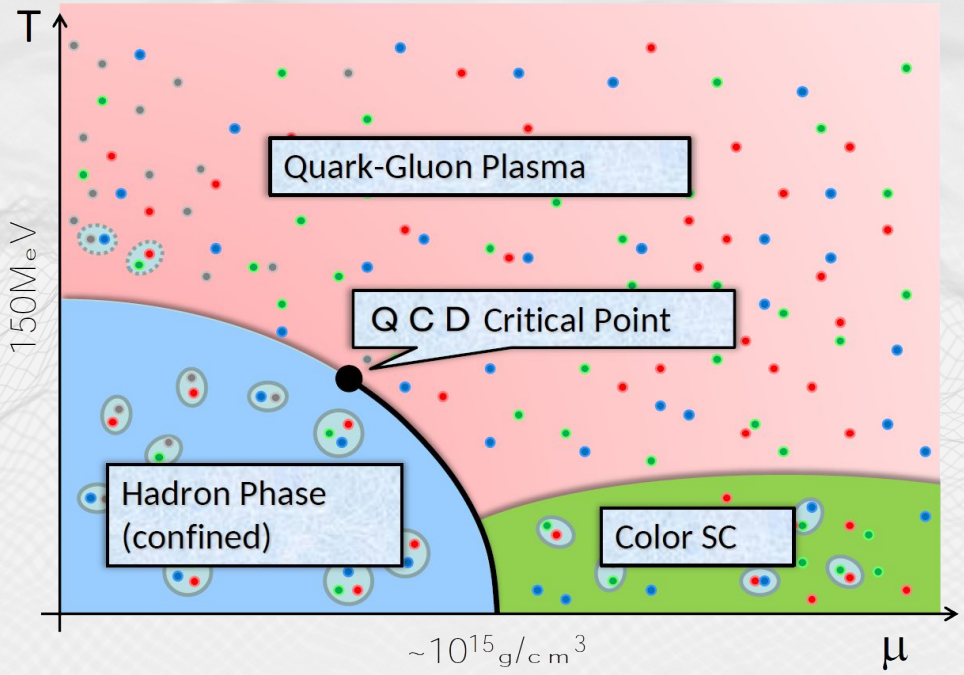


MADAI collaboration, Hannah Petersen and Jonah Bernhard

What are the thermodynamic properties of the strongly interacting matter ?

Introduction

The QCD phase diagram

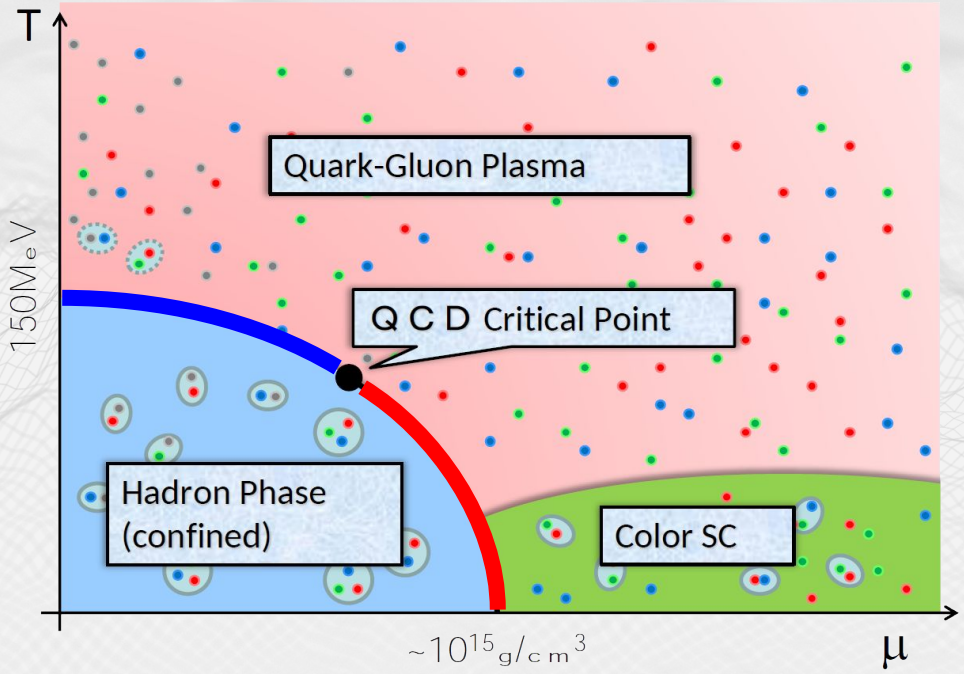


Introduction

The QCD phase diagram

Crossover phase transition

1st order phase transition



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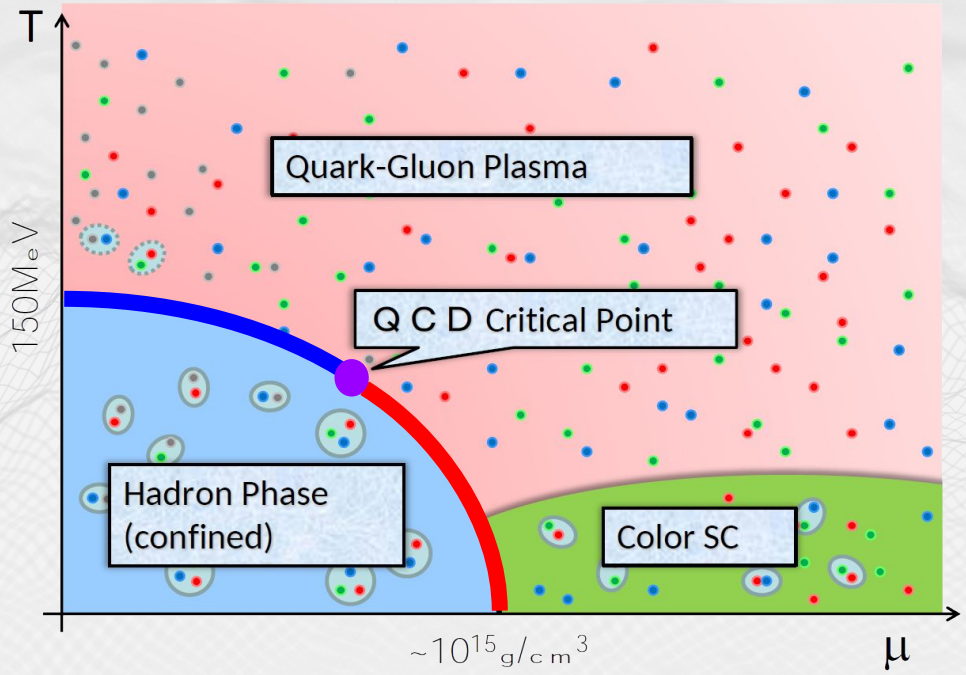
The QCD phase diagram

Crossover phase transition

Critical point

1st order phase transition



Is there a critical point in the QCD phase diagram ?

Introduction

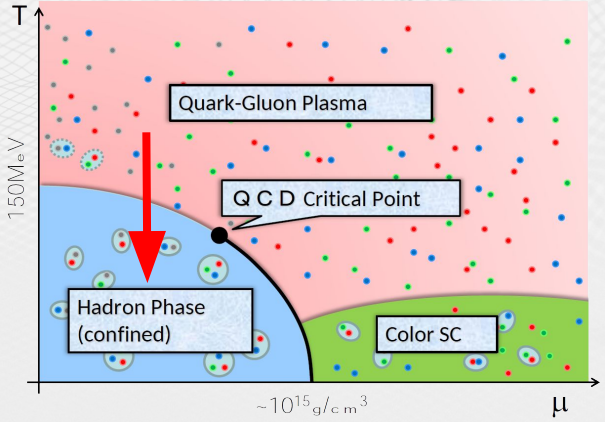
Criticality : Extraordinary effects.

- ➔ Huge net-baryon density fluctuations
- ➔ Infinite correlation length ξ
- ➔ Infinite susceptibility
- ➔ Universal behavior

$$\sigma^2 \sim \xi^2$$
$$S \sim \xi^{4.5}$$
$$\kappa \sim \xi^7$$

M. A. Stephanov, 2008

Dynamics : Rapid expansion and quick temperature decrease

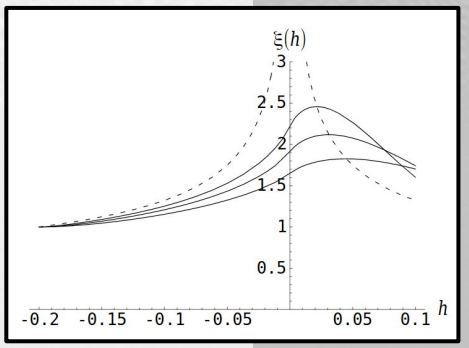


- ➔ Critical slowing down

$$\tau_{relax} \propto \xi^z$$

Hohenberg, Halperin, Rev. Mod. Phys. 49, 435; 1977

- ➔ Non-equilibrium effects

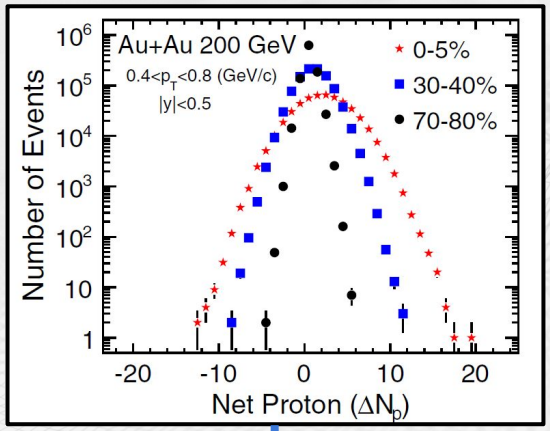


Berdnikov, Rajagopal, MIT-CTP, 1999

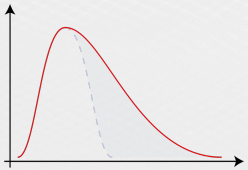
Introduction

$$\sigma^2 \sim \xi^2$$
$$S \sim \xi^{4.5}$$
$$\kappa \sim \xi^7$$

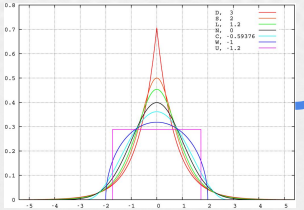
The fluctuations observables can be measured experimentally



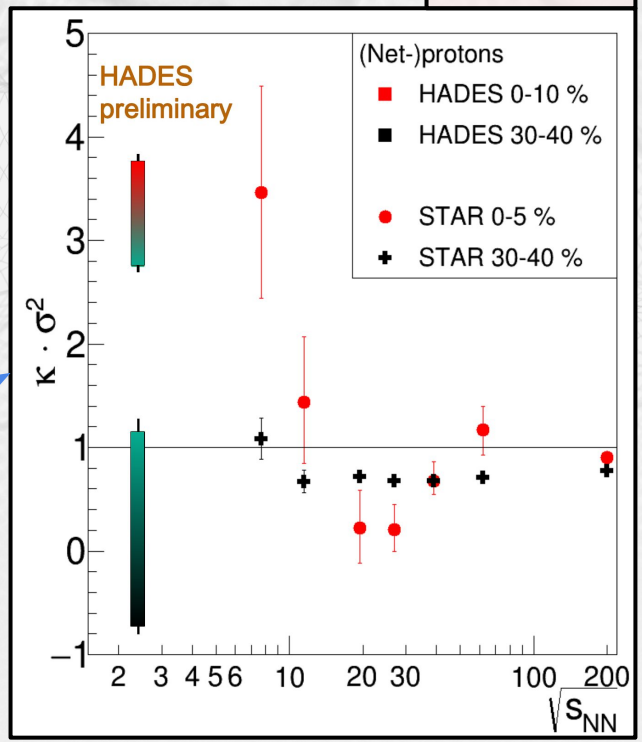
STAR Collab. ~2010



Skewness



Kurtosis



Introduction

- Thermodynamic of QCD matter ?
- Is there a critical point ?
- Extraordinary critical effects
- Rapid expansion and temperature decrease

Introduction

Our work :

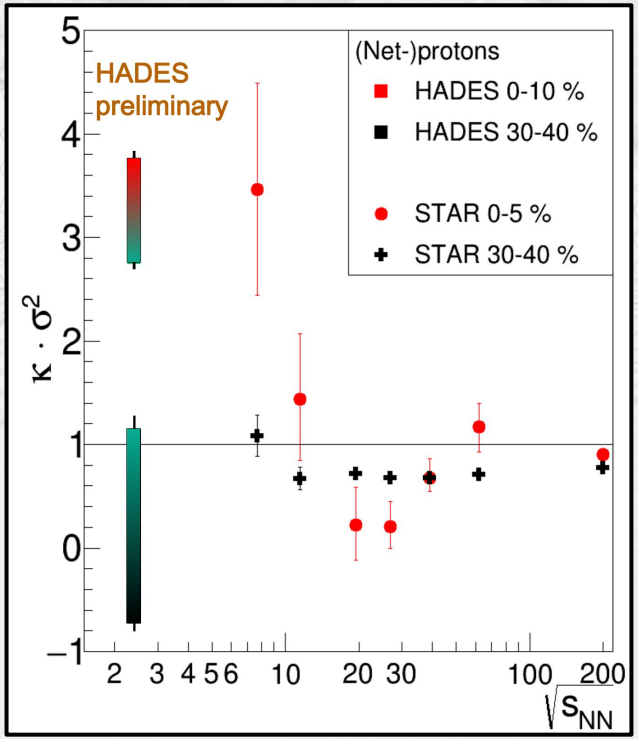
Study the direct impact of the dynamics on the critical fluctuations of the net-baryon density and compute fluctuations related observables

Our goals :

Interpret experimental results on the fluctuations observables

Are they a sign of the QCD critical point ?

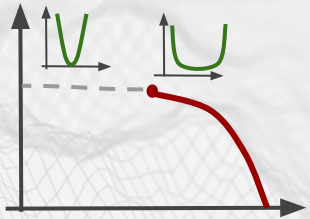
Suggest sensible observables for experimental measurement



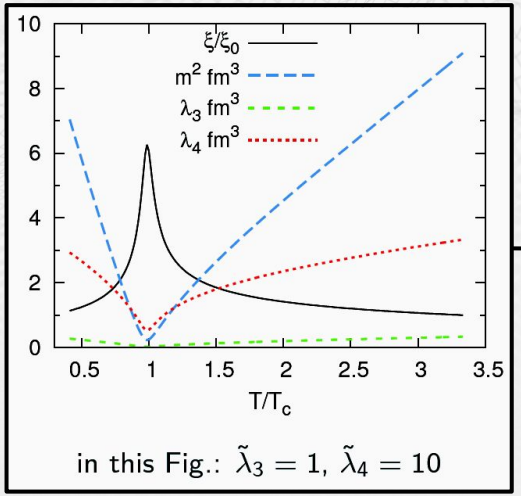
Model for criticality

Ginzburg–Landau free energy functional

$$F(T,\delta n_B) = T\int\left[\frac{m^2(T)}{2\,n_c^{\,2}}\delta n_B^{\,2} + \frac{K}{2\,n_c^{\,2}}\left(\nabla\,\delta n_B\right)^2 + \frac{\lambda_3(T)}{2\,n_c^{\,3}}\delta n_B^{\,3} + \frac{\lambda_4(T)}{2\,n_c^{\,4}}\delta n_B^{\,4} + \frac{\lambda_6}{2\,n_c^{\,6}}\delta n_B^{\,6}\right]\mathrm{d}\vec{x}$$



Temperature parametrization : correlation length given by a mapping from 3D Ising model to the QCD phase diagram



T_c = 0.15 GeV

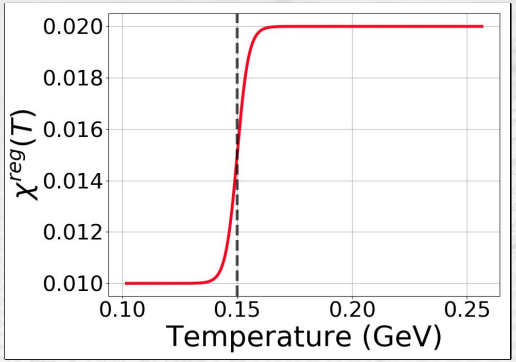
Relation with the correlation length

$$m^2 = 1/(\xi_0\xi^2)$$
$$K = \tilde{K}/\xi_0$$
$$\lambda_3 = n_c\,\tilde{\lambda}_3\,(\xi/\xi_0)^{-3/2}$$
$$\lambda_4 = n_c\,\tilde{\lambda}_4\,(\xi/\xi_0)^{-1}$$
$$\lambda_6 = n_c\,\tilde{\lambda}_6$$

M. Tsypin PRL73 (1994); PRB55 (1997)

Non critical contributions

Parametrization of the susceptibility far from the critical point



M. Sakaida, M. Asakawa, H. Fujii, and M. Kitazawa Phys. Rev. C 95, 064905

$$X(T) = \frac{\chi_2^{B,\,latt}(T)}{s} T^3 \rightarrow \begin{cases} X(T_i) = 0.02\ fm^{-4} \\ X(T_f) = 0.01\ fm^{-4} \end{cases}$$

Asakawa, Heinz, Müller PhysRevLett.85.2072

$$\chi(T) = \frac{n_c^{\,2}}{m^2(T)} \rightarrow m^2{}_{eff}(T)$$

Higher order couplings

In the hadron gas : $\dfrac{\chi_4^{B,latt}(T)}{\chi_2^{B,\,latt}(T)} = 1$

In the QGP : $\dfrac{\chi_4^{B,latt}(T)}{\chi_2^{B,\,latt}(T)} = \dfrac{2}{3\pi^2}$

$$\rightarrow \begin{cases} X_4(T_i) = 0.02\ fm^{-4} \\ X_4(T_f) = 0.001\ fm^{-4} \end{cases} \rightarrow \lambda_{4,\,eff}(T)$$

Dynamics

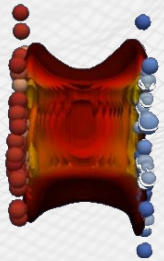
Stochastic diffusion equation :

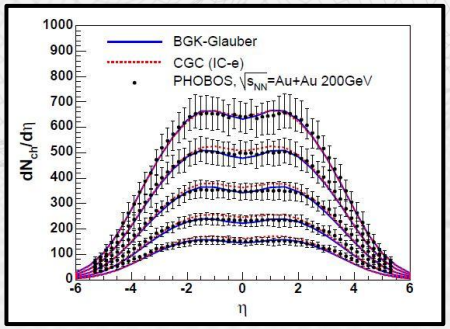
$$\frac{\partial}{\partial t}\delta n_B = D\,\frac{\partial^2}{\partial x^2}\left\{\frac{\delta F}{\delta n_B}\right\} + \frac{\partial}{\partial x}\xi$$

- ➔ Ginzburg-landau
- ➔ Intrinsic white gaussian noise

$$\left\langle \xi(x_1, t_1)\,\xi(x_2, t_2)\right\rangle = 2\kappa T\,\delta(x_1 - x_2)\,\delta(t_1 - t_2)$$

D : diffusion coefficient κ : mobility coefficient





B. B. Back *et al.* Phys. Rev. Lett. 91, 052303

Milne coordinates

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

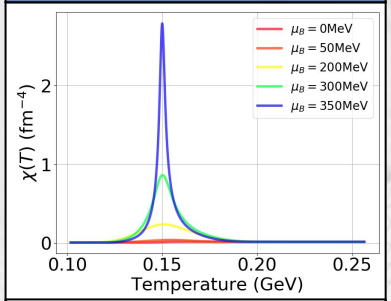
$$y = \frac{1}{2}\ln\left(\frac{t+z}{t-z}\right)$$

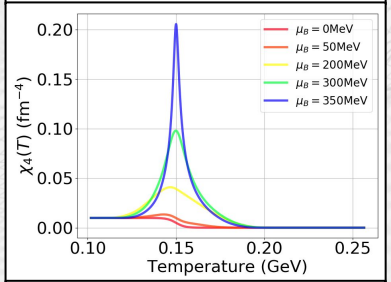
$$\frac{\partial}{\partial \tau}\delta n_B(\tau, y) = D(\tau)\,\frac{\partial^2}{\partial y^2}\left\{\frac{\delta F}{\delta n_B}\right\}(\tau, y) + \frac{\partial}{\partial y}\xi(\tau, y)$$

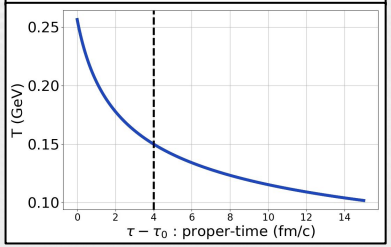
M.Kitazawa, M.Nahrgang, M.Bluhm, N.Touroux, GP, Nuclear Physics A 1005 (2021) 121797
(proceeding Quark Matter 2019)

Selected results : Correlation function

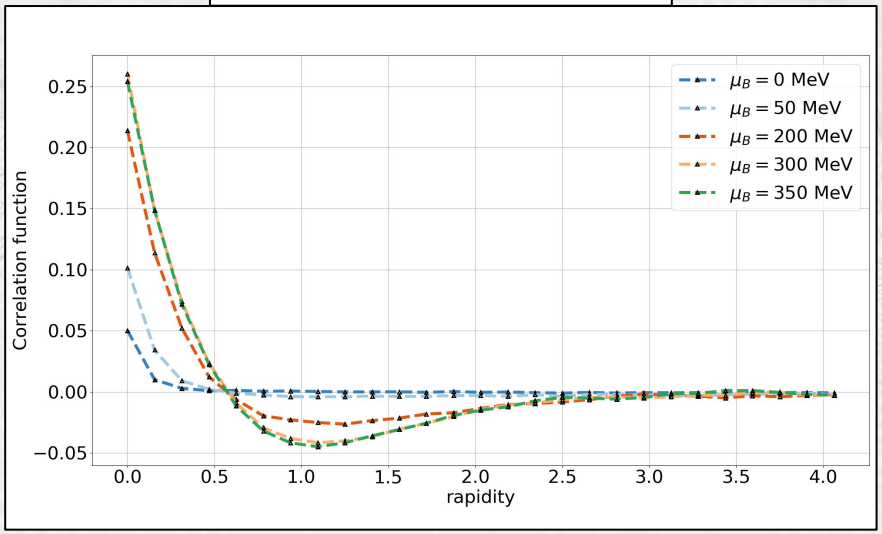
Parametrization





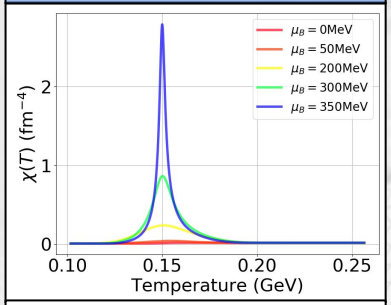


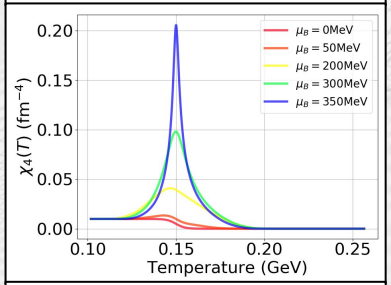
T = 145 MeV

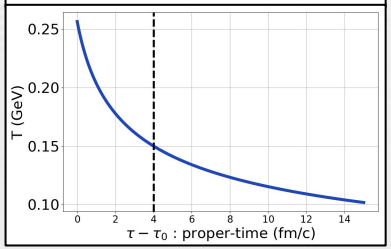


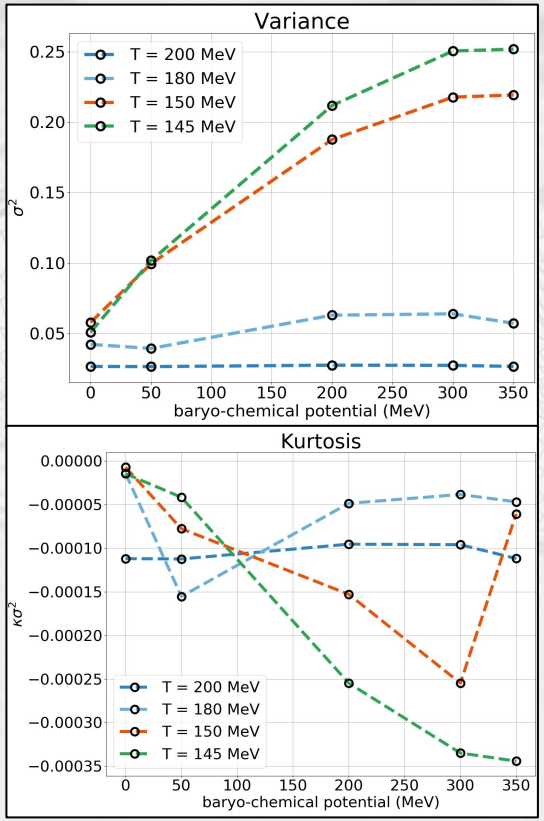
Selected results : Variance and kurtosis

Parametrization









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Interplay of the dynamical and critical effects impact on the fluctuations ?

Model for criticality

- Ginzburg-Landau free energy functional
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Non-critical contributions

- Lattice susceptibilities

Dynamics

- Diffusion equation
- Intrinsic noise
- Milne coordinates

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- Variance & Kurtosis

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