Dynamics of the critical fluctuations in heavy-ion collisions

QGP France - 4th of May 2022

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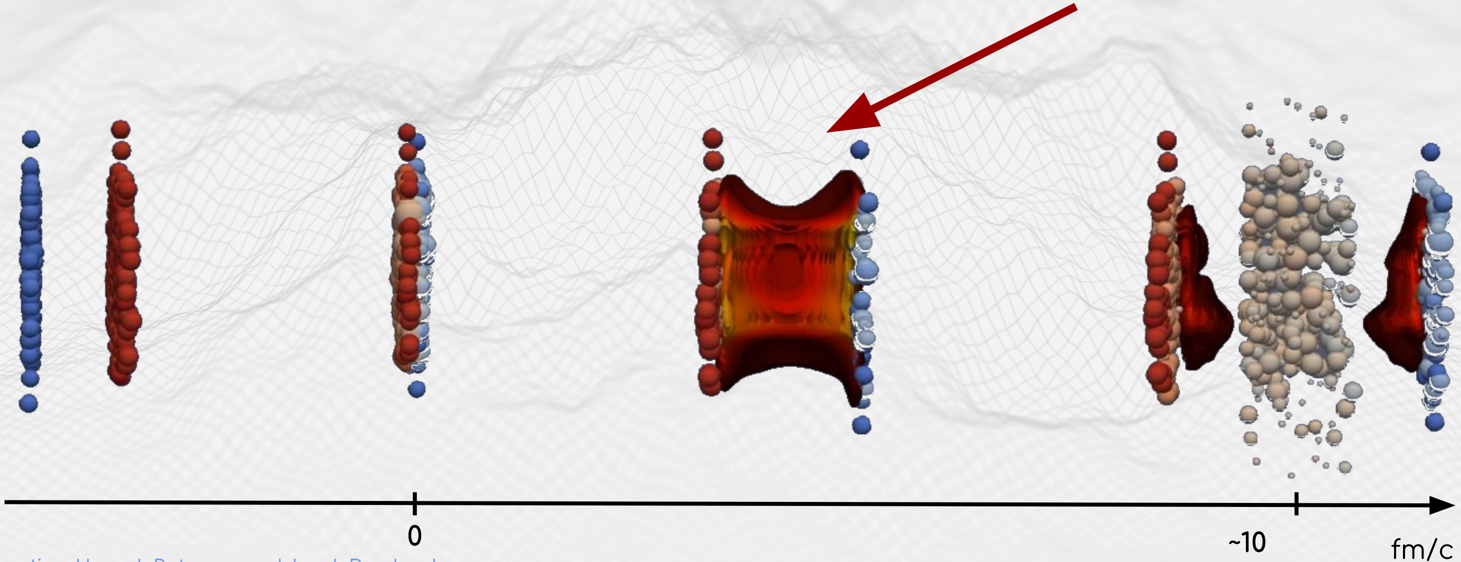
Introduction

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

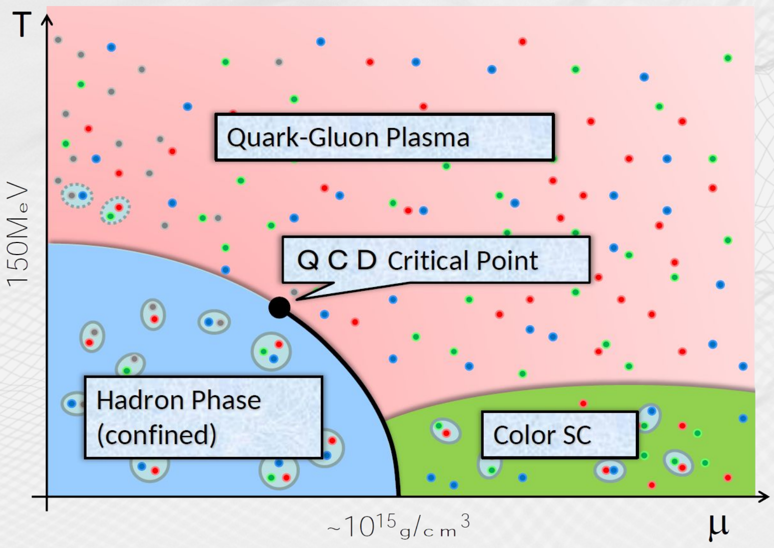


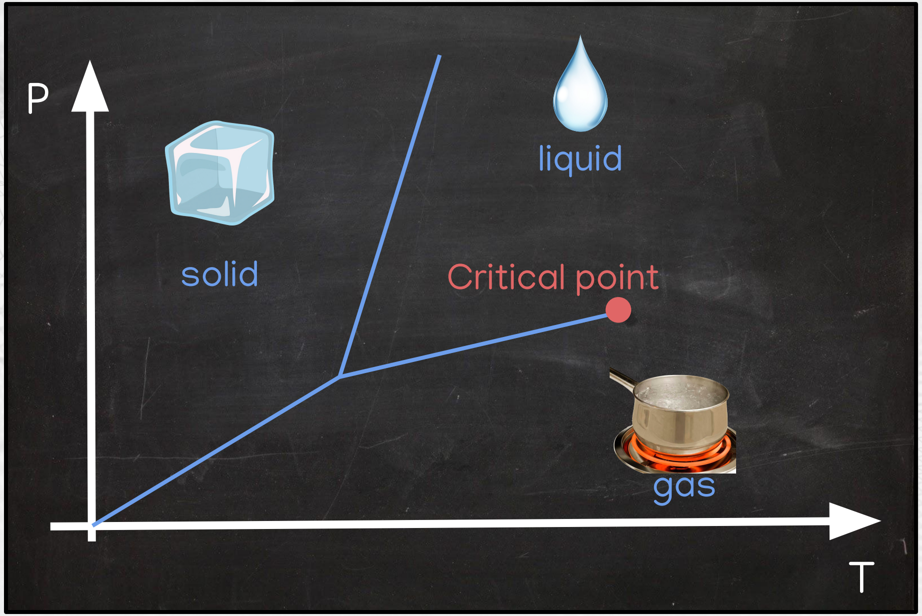
MADAI collaboration, Hannah Petersen and Jonah Bernhard

The matter inside nuclei can be found in various phasis !

Introduction

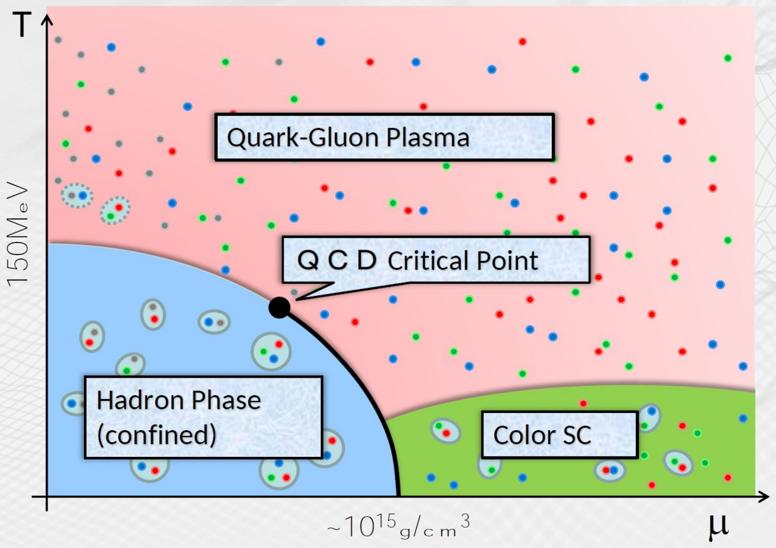
The QCD phase diagram

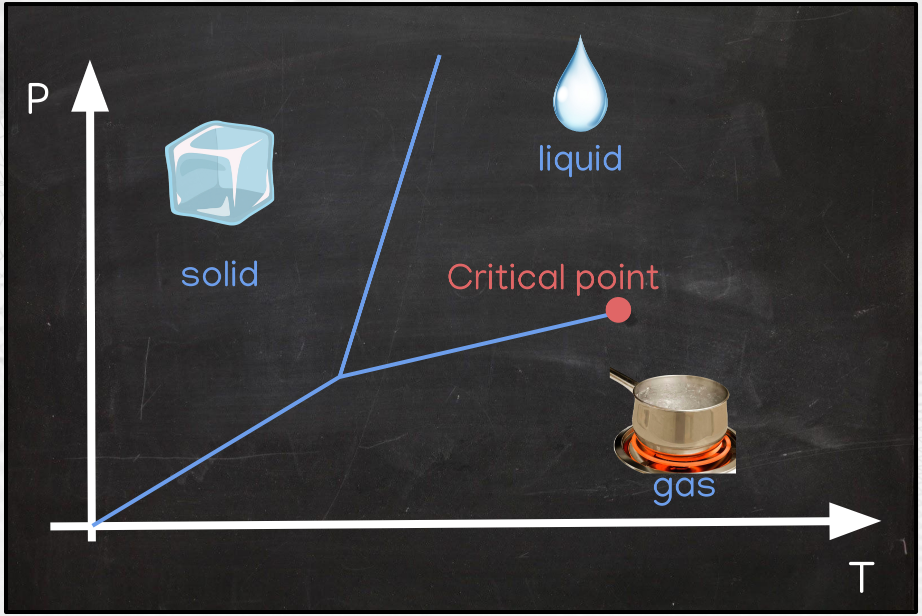




Introduction

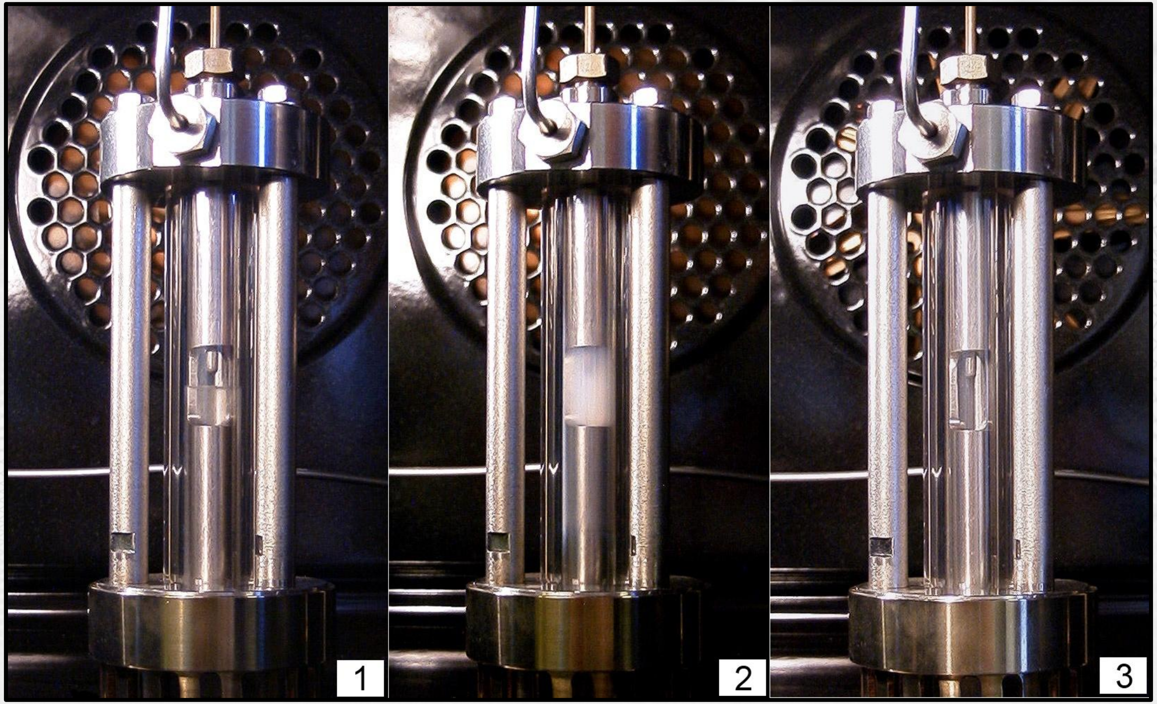
The QCD phase diagram

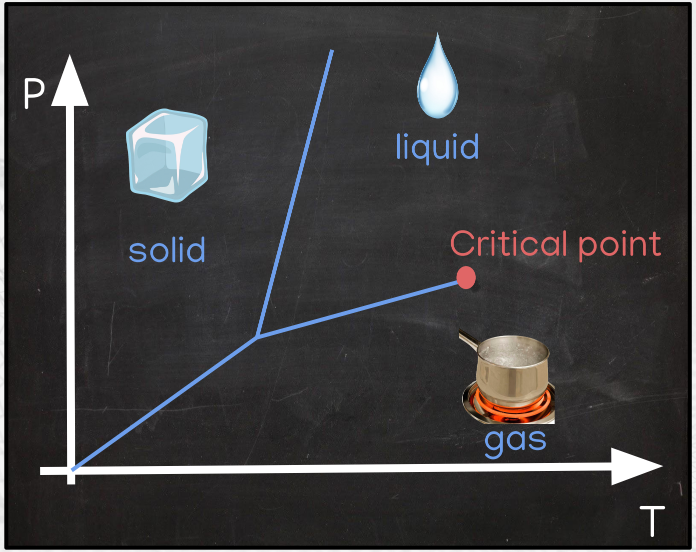




Is there a critical point in the QCD phase diagram ?

Introduction

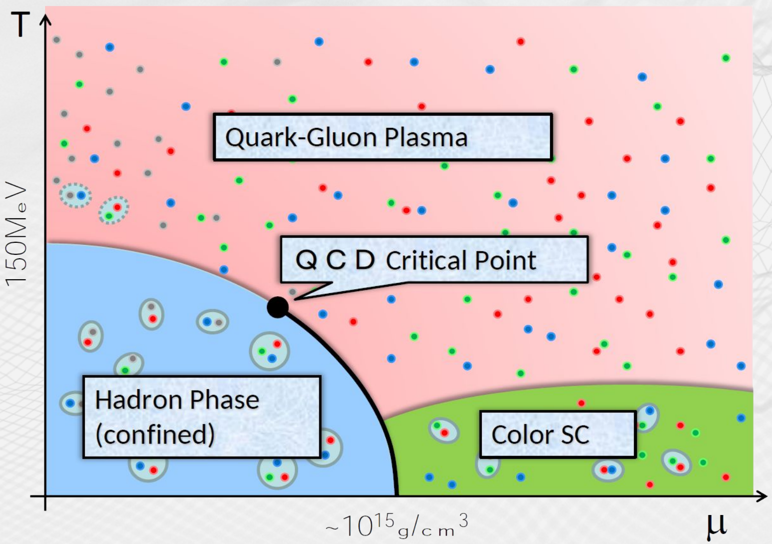




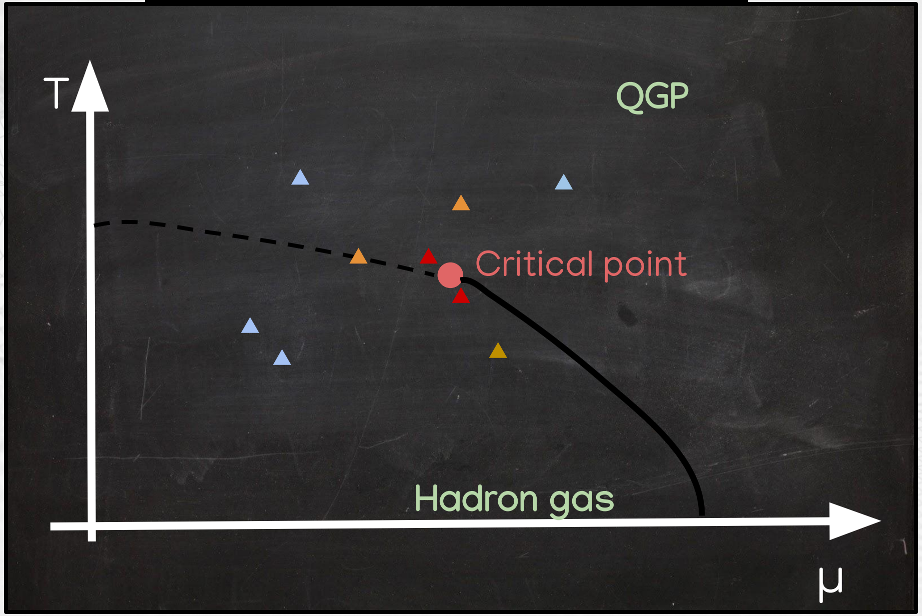
Fluctuations of density are a very relevant probe for criticality !

Introduction

The QCD phase diagram



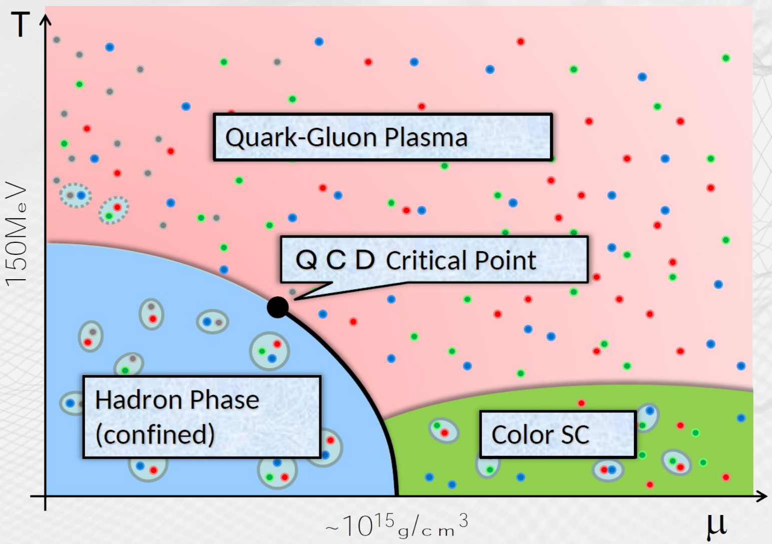
Density fluctuations		
Small	large	Very large

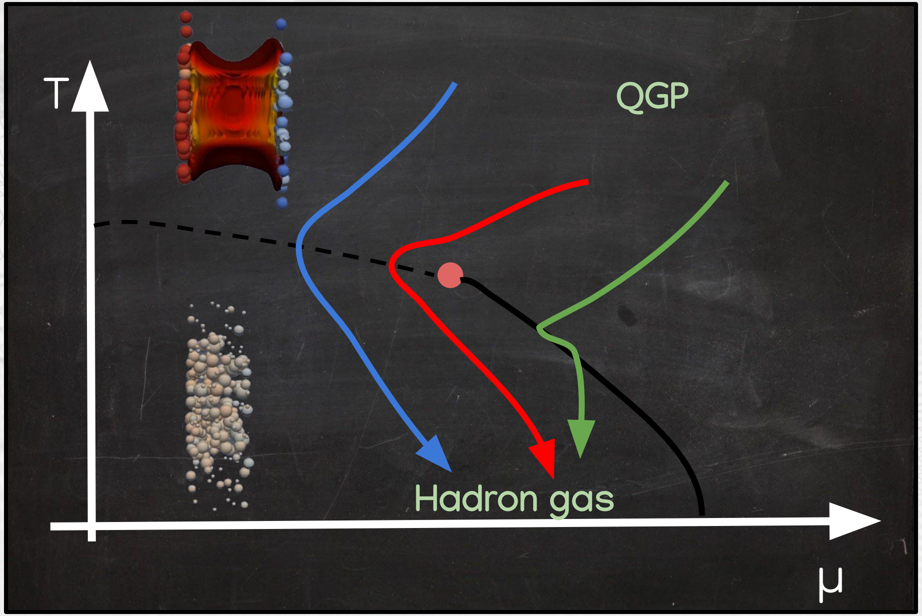


Can we measure the density fluctuations experimentally ?

Yes, with ultra-relativistic heavy-ion collisions !

The QCD phase diagram

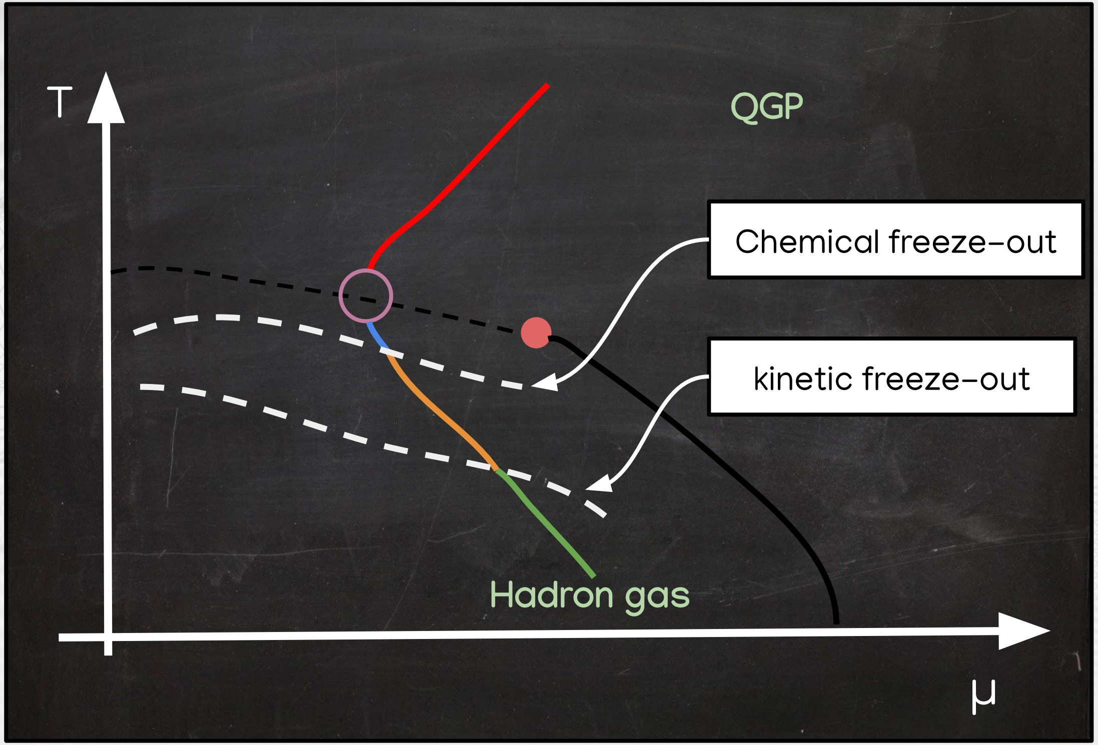




Can we find the critical point using (UR) heavy-ion collisions ?

Introduction

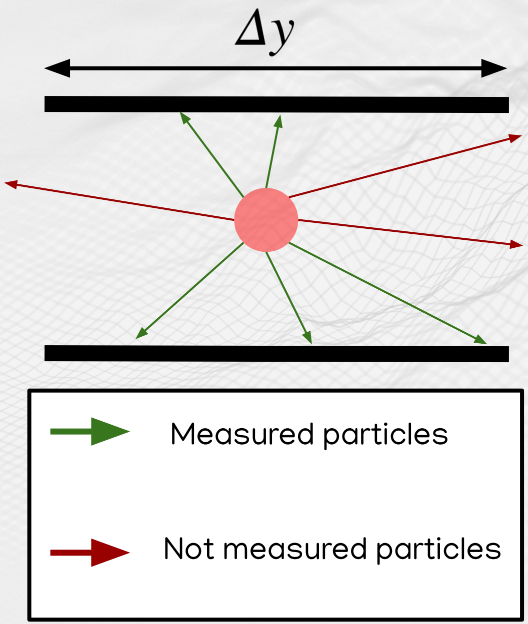
- QGP phase
- Phase transition
- Inelastic interactions
- Elastic interactions
- No more interactions (right to the detector !)

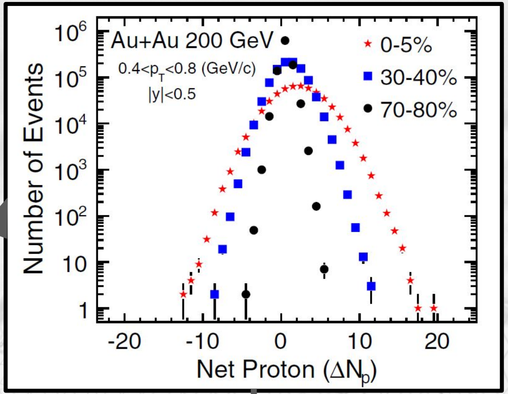


Are we able to measure fluctuations from ◯ and ● after freeze-outs ?

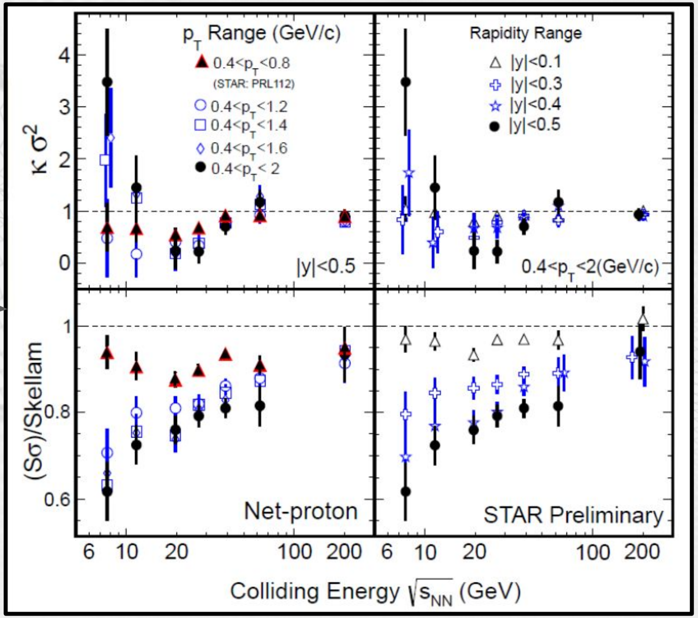
Introduction

The finite size of detectors





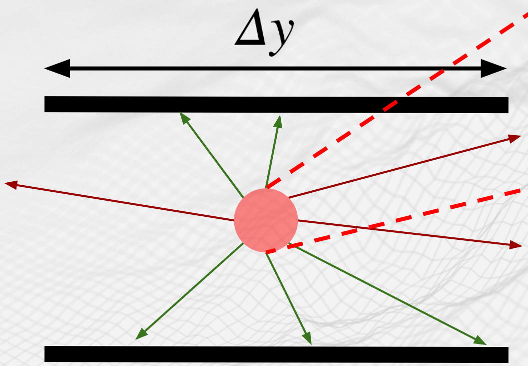
STAR Collab. ~2010



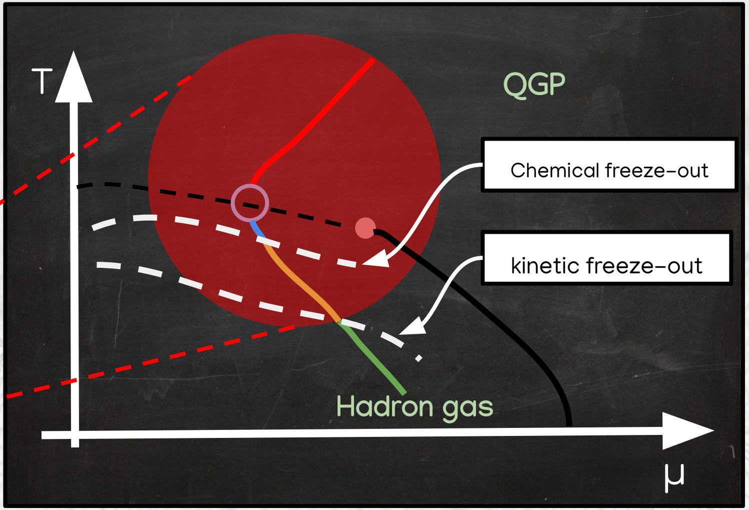
The experimentally measured fluctuations are connected to the density fluctuations at the collision point !

Introduction

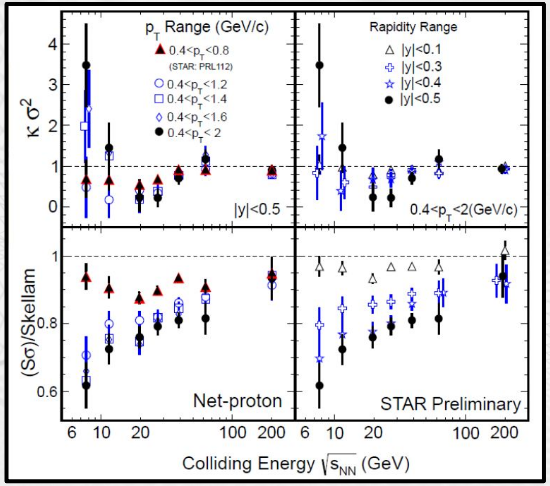
The finite size of detectors



All collisions steps are in the circle !



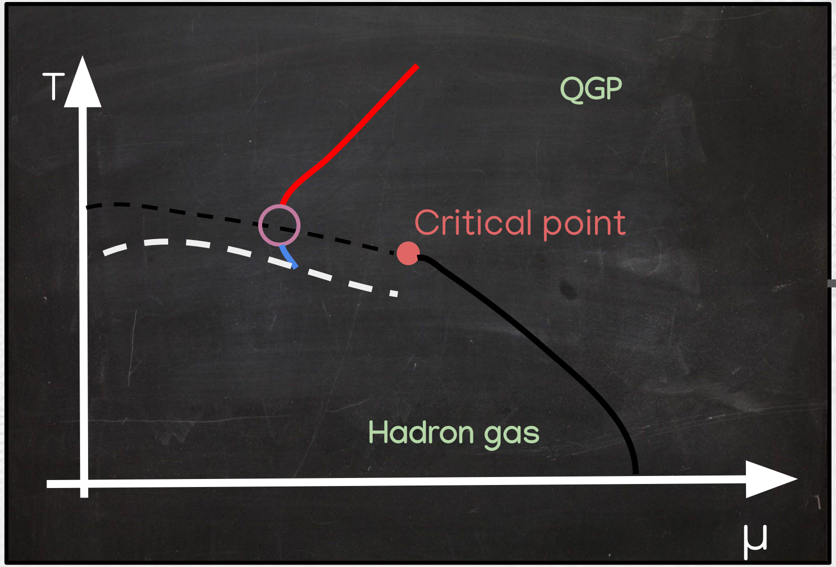
Are the measured fluctuations only related to the critical point ?

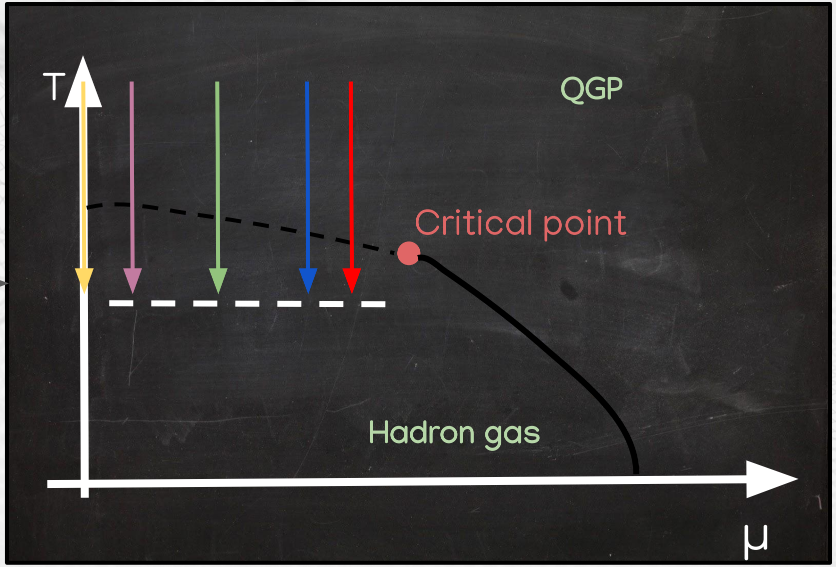


STAR Collab. ~2010

What are the impact of the dynamics on the fluctuations in heavy-ion collisions ?

Introduction





Study the dynamics of net-baryon density critical fluctuations along different trajectories !

Fluctuating fluid dynamics

u^μ : 4-velocity of flow

$\Delta^{\mu\nu} = \eta^{\mu\nu} - u^\mu u^\nu$

Fluctuating fluid dynamics model

Net-baryon number conservation

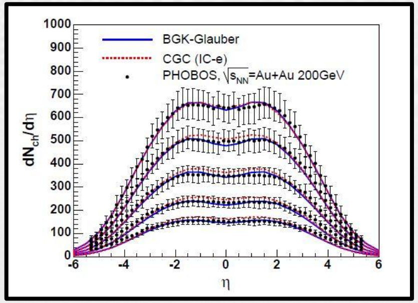
$$\partial_{;\mu} N^\mu_B = 0$$

$$N^\mu_B = n_B u^\mu + \kappa T \Delta^{\mu\nu} \partial_{;\nu} \left\{ \frac{\mu_B}{T} \right\} + \xi^\mu$$

$$\langle \xi^\mu(x) \xi^\nu(x') \rangle = -2\kappa T \delta^{(4)}(x - x') \Delta^{\mu\nu}$$

Bjorken's ansatz

$$u^\mu = \left(\frac{t}{\sqrt{t^2 - z^2}}, \frac{z}{\sqrt{t^2 - z^2}} \right)$$



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

Milne coordinates

Boost-invariance = no dependence on y

proper-time

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

spatial rapidity

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

$$\partial_\tau n_B(\tau, y) = \partial_y \left\{ \frac{\kappa T}{\tau} \partial_y \left\{ \frac{\mu_B}{T} \right\} \right\} + \partial_y \xi^y$$

$$\langle \xi^y(\tau, y) \xi^y(\tau', y') \rangle = 2 \frac{\kappa T}{\tau} \delta(\tau - \tau') \delta(y - y')$$

Stochastic diffusion equation

$$\partial_\tau n_B(\tau, y) = \partial_y \left\{ \frac{\kappa T}{\tau} \partial_y \left\{ \frac{\mu_B}{T} \right\} \right\} + \partial_y \xi^y$$
$$\langle \xi^y(\tau, y) \xi^y(\tau', y') \rangle = 2 \frac{\kappa T}{\tau} \delta(\tau - \tau') \delta(y - y')$$

Assumptions

Constant diffusion coefficient D

$$\kappa T = D$$

The baryochemical potential is given by a Ginzburg–Landau type free-energy functional

$$\mu_B = \frac{\delta \mathcal{F}}{\delta n_B}$$

$$\partial_\tau n_B = D(\tau) \partial_y^2 \left\{ \frac{\delta \mathcal{F}/T}{\delta n_B} \right\} + \partial_y \xi^y$$

$$\langle \xi^y(\tau, y) \xi^y(\tau', y') \rangle = 2 D(\tau) \delta(\tau - \tau') \delta(y - y')$$

$$D(\tau) = \frac{D}{\tau}$$

The free-energy functional encodes the critical physics

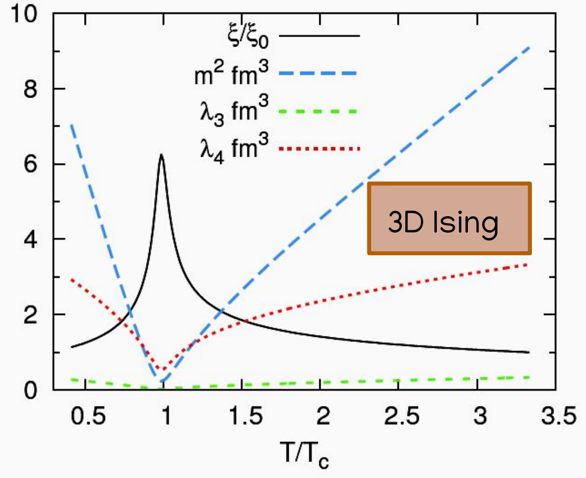
The diffusion coefficient is a tool to study the impact of the dynamics on the fluctuations

Free-energy functional

$$\mathcal{F}(\tau) = \int \mathrm{d}\mathcal{V}\Big\{\frac{n_B^2}{2\chi_2(\tau)} + \frac{K(\tau)}{2}(\partial_y n_B)^2 + \frac{n_B^4}{24\chi_4(\tau)}\Big\}$$

$$T(\tau) = T_i\left(\frac{\tau_0}{\tau}\right)$$

Critical contribution



in this Fig.: $\tilde{\lambda}_3 = 1,\ \tilde{\lambda}_4 = 10$

M. Nahrgang, M. Bluhm **Phys. Rev. D 102, 094017**

M. Nahrgang, M. Bluhm, T. Schäfer, S.A Bass **Phys. Rev. D 99, 116015**

Non-critical contribution

Lattice QCD

$$\frac{\chi_2^B}{s}T^3$$

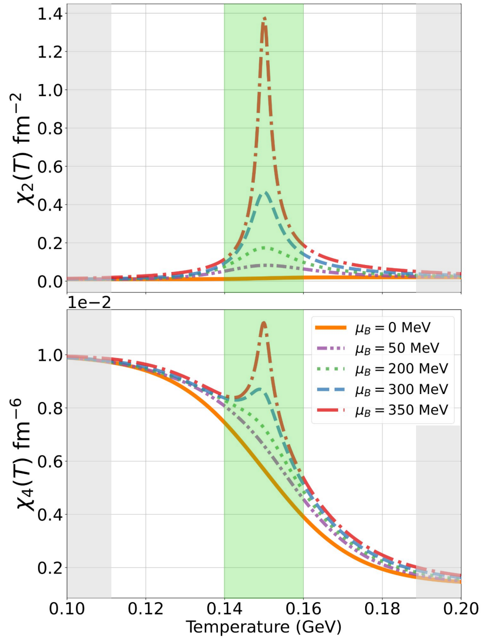
$$\chi_n^{\mathrm{reg}}(T) = \chi_{0,n}^{\mathrm{H}} + \left(\chi_{0,n}^{\mathrm{QGP}} - \chi_{0,n}^{\mathrm{H}}\right)S(T)$$

	Hadron gas	QGP
χ_2	0.01 fm^{-2}	0.02 fm^{-2}
χ_4	0.01 fm^{-6}	0.01 fm^{-6}

Asakawa, Heinz, Müller PhysRevLett.85.2072

M. Cheng et al Phys. Rev. D 79, 074505

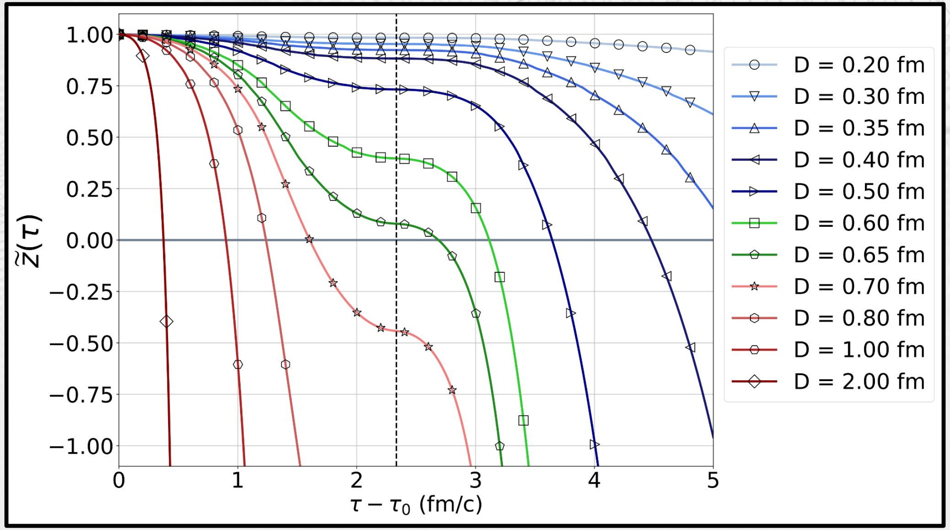
A.Bazazov et al Phys. Rev. D 95, 054504



The diffusion coefficient

In the scaling region

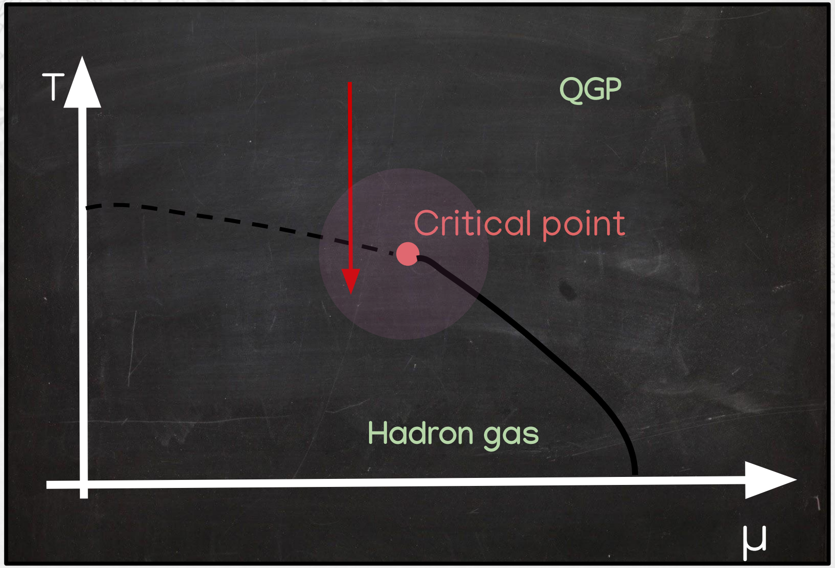
$$D \propto \frac{1}{\tau_r}$$



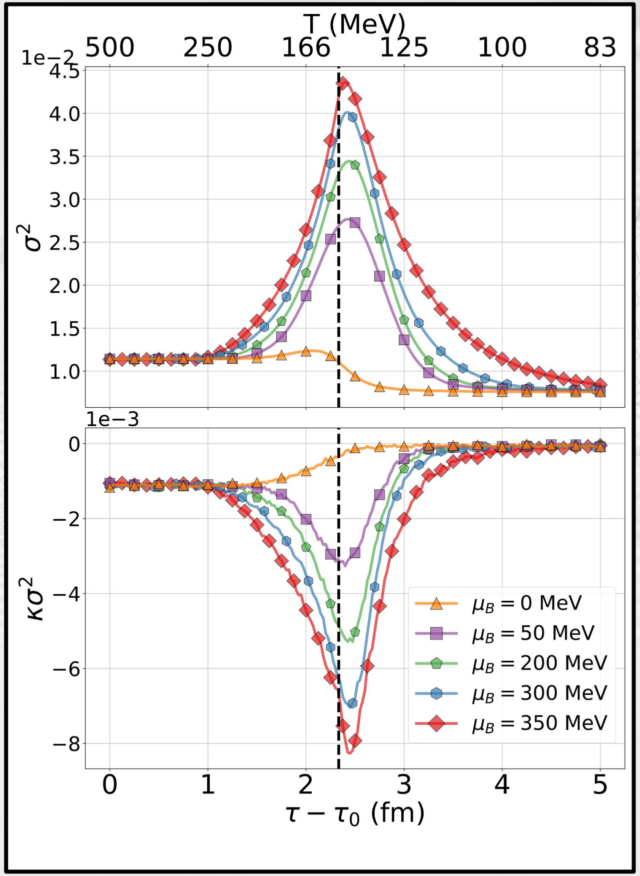
GP, Bluhm, Kitazawa, Nahrgang, CPOD2021 Proceeding arXiv:2111.14466 [nucl-th]

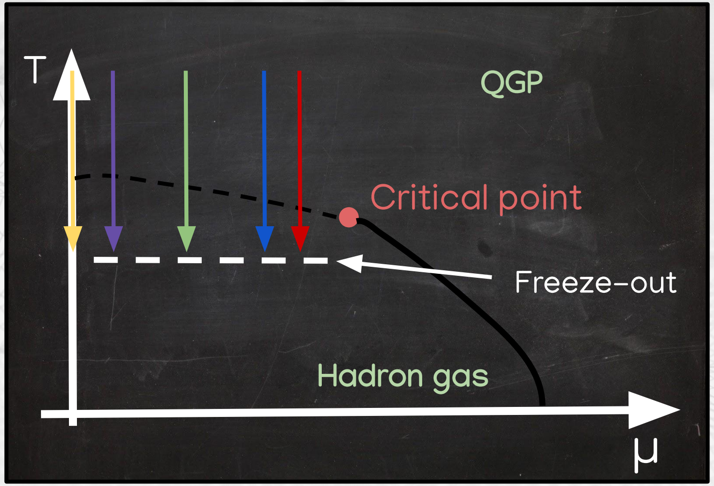
Diffusion coefficient

$$\partial_\tau n_B = D(\tau)\partial_y^2\left\{\frac{\delta\mathcal{F}/T}{\delta n_B}\right\} + \partial_y \xi^y$$



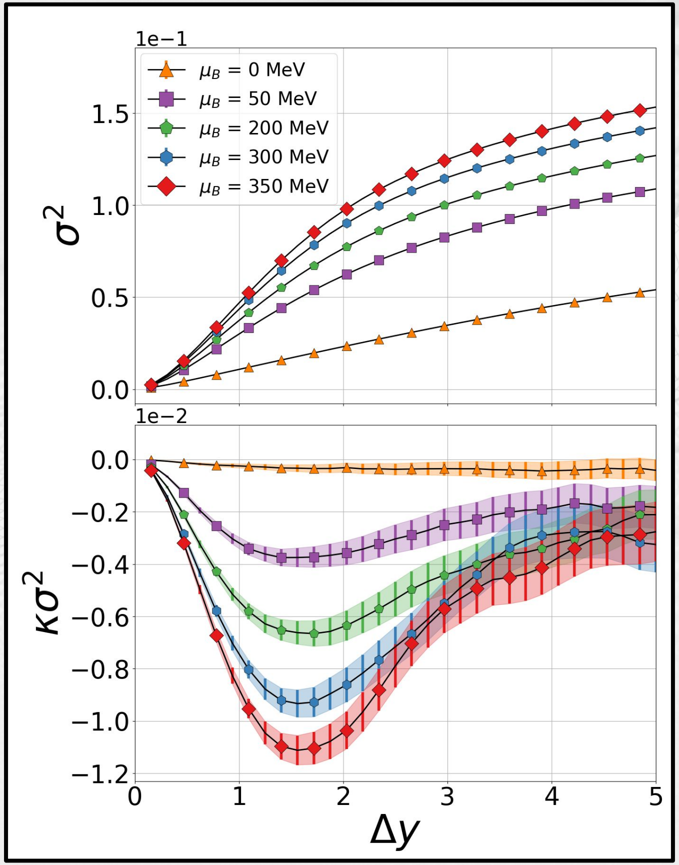
time-dependence of variance and the kurtosis



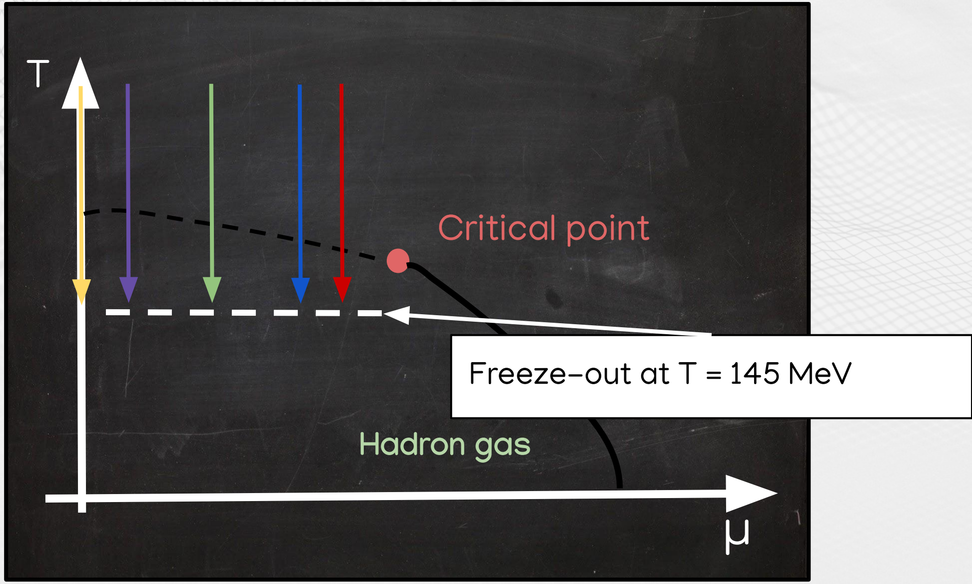


- Enhancement of the fluctuations due to the critical point !
- The signal is very sensitive to the freeze-out temperature.

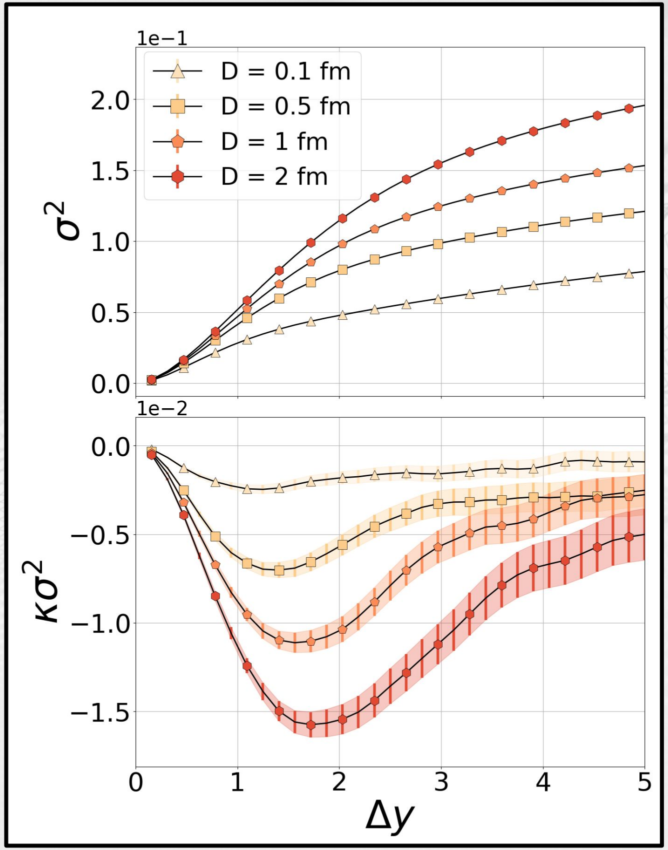
Rapidity window dependence of the variance and kurtosis



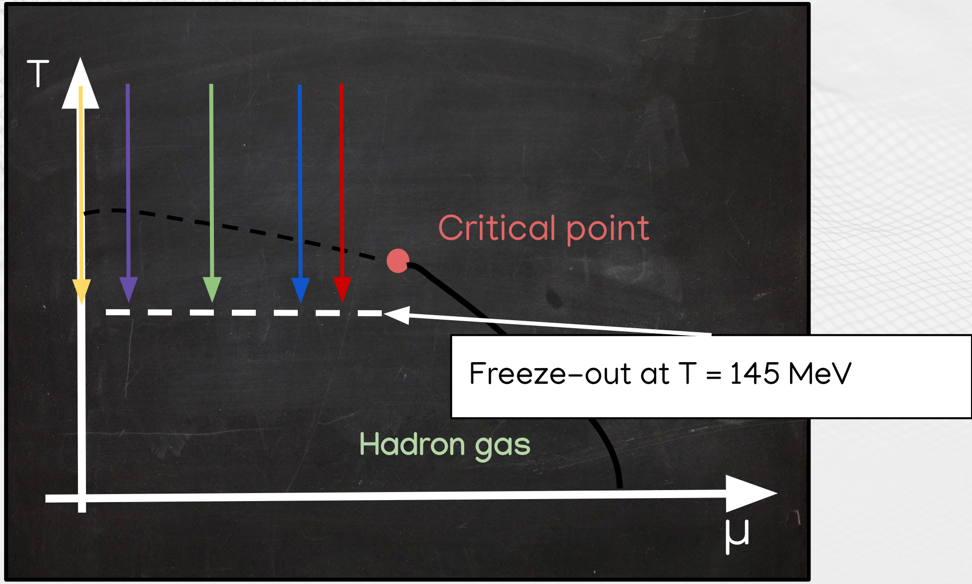
$$n_{B,i}(\Delta y) = \int_{-\Delta y/2}^{\Delta y/2} dy \; n_{B,i}$$



Rapidity window dependence of the variance and kurtosis



The cumulants are very sensitive to the diffusion length

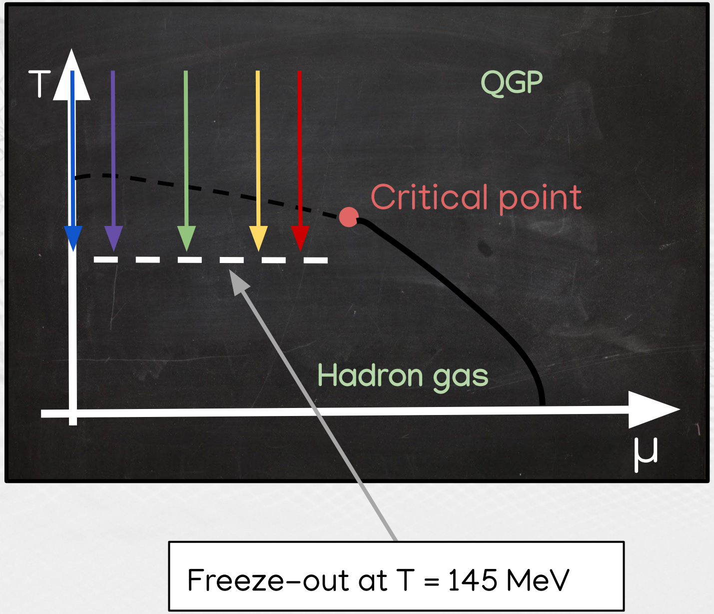


Conclusion

- A critical signal can be observed !

- The signal is very sensitive to the freeze-out temperature.

- The signal is very sensitive to diffusion length.



Need more reliable values for the diffusion length and freeze-out parameters.
Proper particilization is needed !