Z. Physik A286, 121 – 122 (1978)

Zeitschrift für Physik A

Short Note

Dependence of Particle Production in High Energy Heavy Ion Collisions on the Nuclear Equation of State

Horst Stöcker and Walter Greiner
Institut für Theoretische Physik der Johann Wolfgang Goethe Universität, Frankfurt am Main

Werner Scheid
Institut für Theoretische Physik der Justus Liebig Universität, Gießen

Received February 20, 1978

Abstract: The total pion production cross section in central high energy heavy ion collisions depends strongly on the nuclear equation of state. This fact can be used to detect phase transitions from normal nuclear matter into abnormal superdense states (density isomers).

the additional production of free pions due to the collision dynamics. For our model, we need the mean energy per nucleon $W(\rho,T)$ and the internal pressure $p(\rho,T)$: For $W(\rho,T)$ we use the ansatz

$$W(\rho,T) = W_o + E_C(\rho) + E_T(\rho,T) + \Delta Mc^2(T) + E_\pi(\rho,T)$$

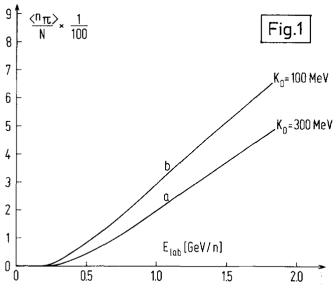


Fig.1
⟨nπ⟩/N × 1/100
K0 = 100 MeV
K0 = 300 MeV
b
a
E lab [GeV/n]

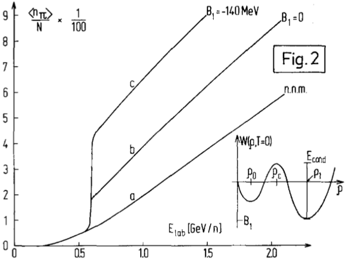


Fig. 2
⟨nπ⟩/N × 1/100
B1 = -140 MeV
B1 = 0
n.n.m.
c
b
a
E lab [GeV/n]
W(ρ,T=0)
E cond
ρ0
ρc
ρ1
ρ
B1

Pion production at the QCD phase transition

Christoph Herold
with T. Bumnedpan, J. Steinheimer, M. Bleicher

Phys. Lett. B **835**, 2022 [arXiv:2209.04096]

Center of Excellence in High Energy Physics & Astrophysics,
School of Physics, Suranaree University of Technology

MAGIC23 workshop, Kovalam, Krabi

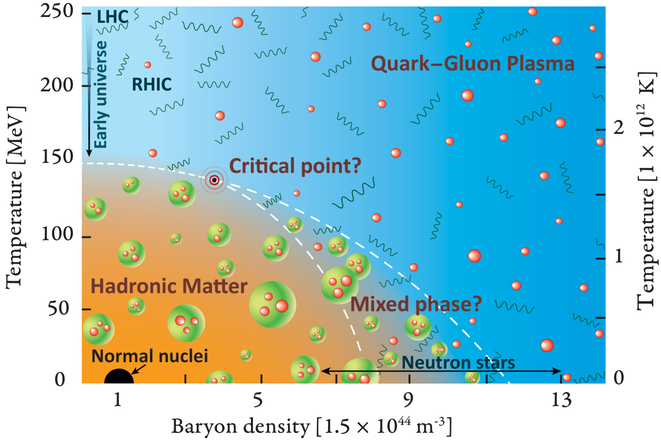
Center of Excellence in High-Energy Physics and Astrophysics

Center of Excellence in High-Energy Physics and Astrophysics

Center of Excellence in High-Energy Physics and Astrophysics

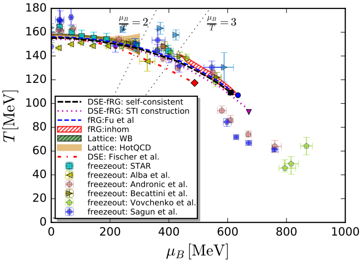
Outline

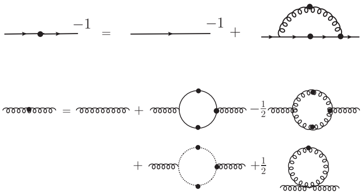
The QCD Phase Diagram



First principle calculations

- Partition function $\mathcal{Z}$ on a lattice (sign problem for finite μ)
- Solve Dyson-Schwinger equations

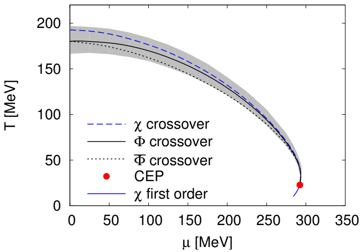




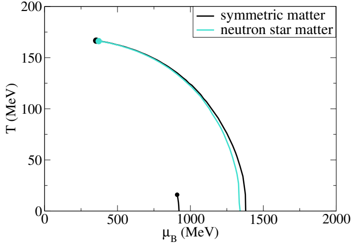
(Gao, Pawlowski, Phys. Lett. B **820**, 2021)

Effective Models

- Start with (chiral) symmetry, sigma, NJL model
- Extension with Polyakov loop, baryonic degrees of freedom
- Existence/location of CP not universal



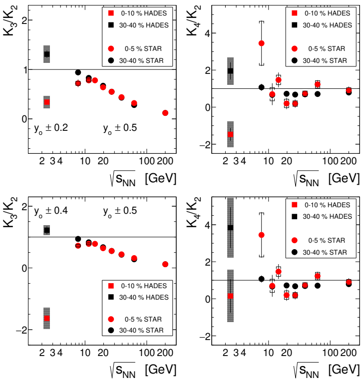
(Herbst, Pawlowski, Schaefer, Phys. Lett. B **696**, 2011)



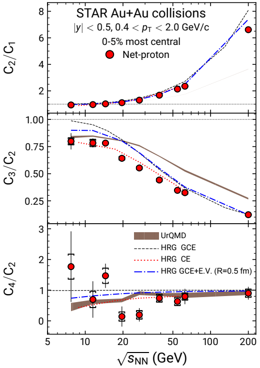
(Dexheimer, Schramm, Phys. Rev. C **81**, 2010)

Critical Point - Signals and Observables

1. Higher order cumulants: HADES and STAR data



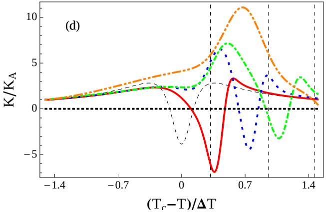
(HADES coll., Phys. Rev. C **102**, 2020)



(STAR coll., Phys. Rev. C **104**, 2021)

Critical Point - Signals and Observables

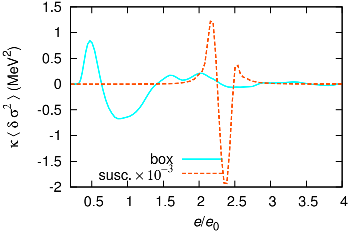
2. Nonequilibrium effects

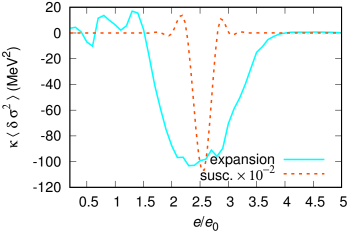


(Mukherjee, Venugopalan, Yin, Phys. Rev. C **92**, 2015)

Cumulants are influenced by:

- Dependence on ξ
- Relaxation time
- Inhomogeneities





(CH, Nahrgang, Bleicher et al., EPJ A**54**, 2018)

Critical Point - Signals and Observables

- Determine cumulants of the 0-mode of the sigma field at freeze-out

$$\sigma_V = \int_V \mathrm{d}^3 x \sigma(x) = \sigma V$$

- Net-proton number fluctuations from Poisson plus critical fluct.

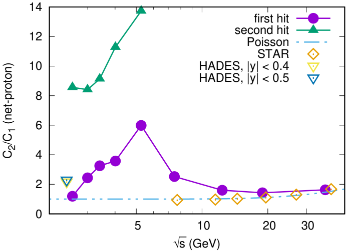
$$\delta N = \delta N^0 + V\, g\, \delta\sigma\, d \int \frac{\mathrm{d}^3 p}{(2\pi)^3} \frac{\partial n_p}{\partial m}$$

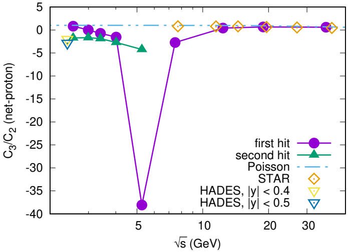
- Relate net-proton to sigma cumulants

$$\langle (\delta N)^4 \rangle_c = \langle N \rangle + \langle \sigma_V^4 \rangle_c \left(\frac{g\, d}{T} \int \frac{\mathrm{d}^3 p}{(2\pi)^3} \frac{n_p}{\gamma} \right)^4 + \ldots,$$

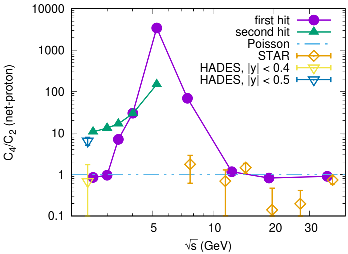
(Stephanov, Phys. Rev. Lett. **107**, 2011)

Critical Point - Signals and Observables





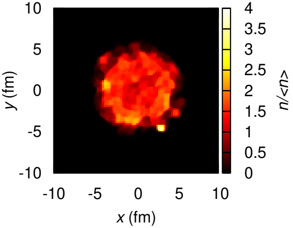
- Poisson baseline approached for large $\sqrt{s}$
- Strongly enhanced cumulants near spinodal line
- FOPT allows for wider range of cumulants

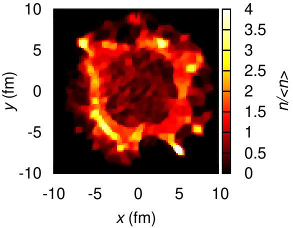


(CH, Saikham et al., Phys. Rev. C **106**, 2022)

First-order Phase Transition - Signals and Observables

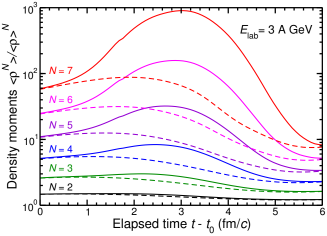
1. Nonequilibrium effects: Spinodal instabilities





(CH, Nahrgang et al., Nucl. Phys. A **925**, 2014)

- Formation of Metastable phase
- Dynamical fragmentation
- Non-statistical multiplicity fluctuations
- Signal in momentum space?

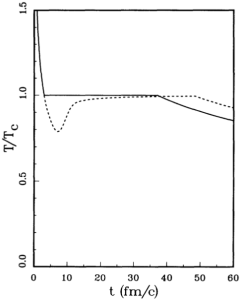


(Steinheimer, Randrup, Phys. Rev. Lett. **109**, 2012)

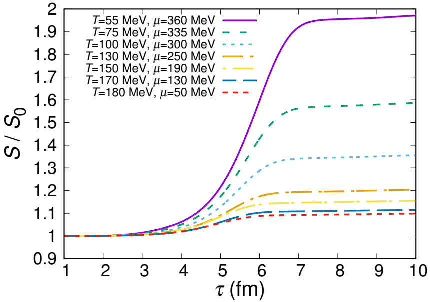
First-order Phase Transition - Signals and Observables

2. Delayed Expansion

- Thermal radiation, dileptons
- Hanbury-Brown-Twiss Interferometry
- Generation of **Extra entropy** from nonequilibrium phase transition



(Csernai, Kapusta, Phys. Rev. Lett. **69**, 1992)

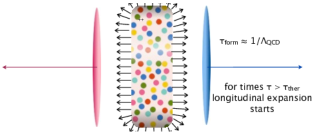


(CH, Kittiratpattana et al., Phys. Lett. B **790**, 2019)

NχFD

Nonequilibrium Chiral Fluid Dynamics (**NχFD**)

- Nonequilibrium dynamics of σ
- Fluid dynamic expansion
- damping and stochastic noise



(G. Martinez, arXiv:1304.1452)

$$\ddot{\sigma} + \eta\dot{\sigma} + \frac{\delta\Omega}{\delta\sigma} = \xi$$

$$\dot{e} = -\frac{e+P}{\tau} + \left(\frac{\delta\Omega}{\delta\sigma} + \eta\dot{\sigma}\right)\dot{\sigma} \;, \quad \dot{n} = -\frac{n}{\tau}$$

(CH, Kittiratpattana, Kobdaj, Limphirat, Yan, Nahrgang, Steinheimer, Bleicher, Phys. Lett. B **790**, 2019)

$$\mathcal{L} = \bar{q}\left(i\gamma^\mu\partial_\mu - g\sigma\right)q + \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - U(\sigma)$$

Lagrangian of the quark-meson model

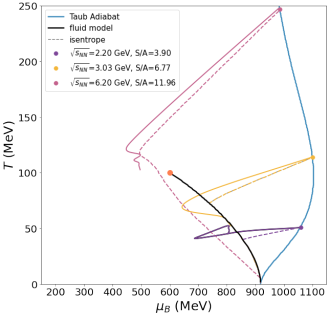
Initial Conditions

- Realistic initial conditions
- 1D shock wave solution (Rankine-Hugoniot-Taub adiabat)

$$(P_0+\varepsilon_0)\,(P+\varepsilon_0)\,n^2 = (P_0+\varepsilon)\,(P+\varepsilon)\,n_0^2$$

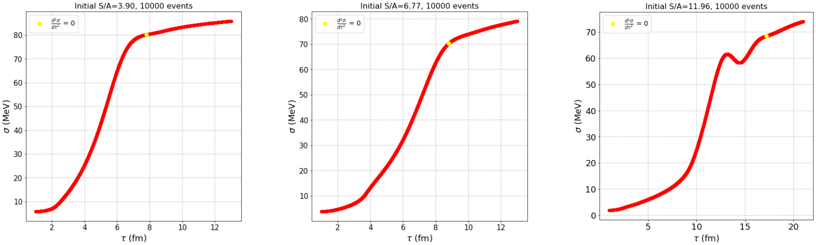
- Relate collision energy from compression:

$$\gamma^{\mathrm{CM}} = \frac{\varepsilon n_0}{\varepsilon_0 n},\ \gamma^{\mathrm{CM}} = \sqrt{\frac{1}{2}\left(1+\frac{E_{\mathrm{lab}}}{m_N}\right)}$$



(Bumnedpan, CH, JS, MB, Phys. Lett. B **835**, 2022)

"Freeze-out" condition



Test different freeze-out criteria depending on the evolution of σ

- Freeze-out at constant value of $\sigma = 70$ MeV
- Freeze-out at "end" of the rapid transition, i.e. $\mathrm{d}^2\sigma/\mathrm{d}\tau^2 = 0$

Fit to chemical freeze-out curves

- Use two parametrized freeze-out curve obtained from hadron multiplicity ratios

$$T_{\mathrm{freeze}}(\mu_B) = a - b\mu_B^2 - c\mu_B^4$$

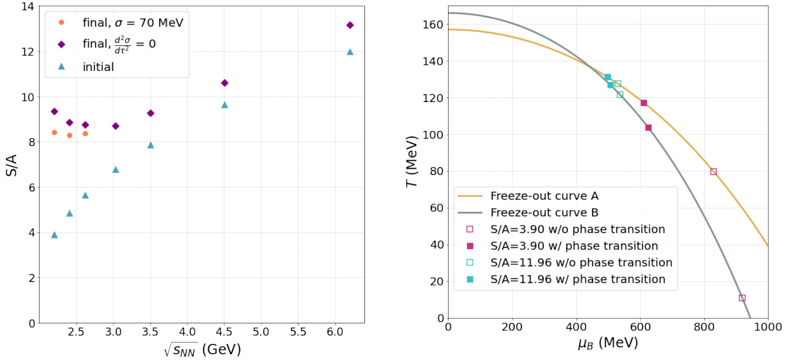
- Parameter set A:
  $a = 0.157$ GeV, $b = 0.087$ GeV^{-1} and $c = 0.092$ GeV^{-3}

  (Vovchenko, Begun, Gorenstein, Phys. Rev. C **93**, 2016)

- Parameter set B:
  $a = 0.166$ GeV, $b = 0.139$ GeV^{-1} and $c = 0.053$ GeV^{-3}

  (Cleymans, Oeschler, Redlich, Wheaton, Phys. Rev. C **73**, 2006)

Entropy per baryon number

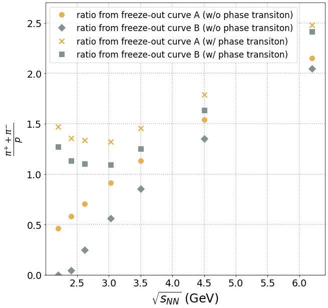


(Bumnedpan, CH, JS, MB, Phys. Lett. B **835**, 2022)

- Qualitatively similar results for S/A, slight deviations at low $\sqrt{s}$
- Fit to freeze-out curves using Thermal-FIST HRG toolkit

(Vovchenko, Stoecker, Comput. Phys. Commun. **244**, 2019)

Pion-to-proton ratio

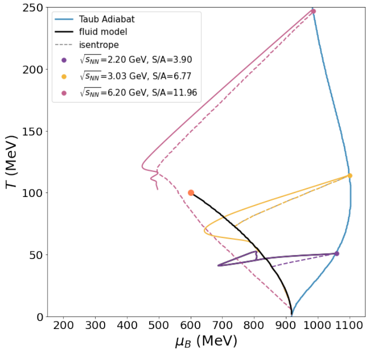


(Bumnedpan, CH, JS, MB, Phys. Lett. B **835**, 2022)

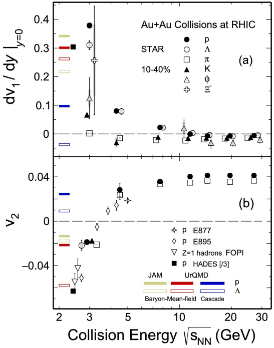
- Pion-to-proton ratio as observable for S/A
- FOPT scenario leads to increase at low $\sqrt{s}$
- In the model: Initial state always in restored phase
- Realistically: Jump in π/p at onset of chiral PT, around ~ 3 GeV

(STAR, Phys. Lett. B **827**, 2022)

Caveats and what to look for



(Bumnedpan, CH, JS, MB, Phys. Lett. B **835**, 2022)

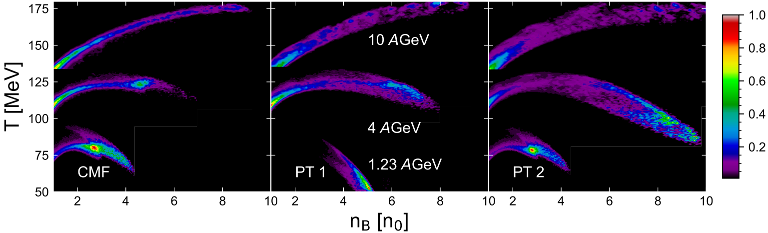


(STAR coll., Phys. Lett. B **827**, 2022)

- Model caveat: Initial state always in the restored phase
- Measurements of v_1, v_2 at STAR suggest dominance of baryons for $\sqrt{s_{NN}} \lesssim 3$ GeV
- Expect jump in π/p at onset of chiral PT around ~ 3 GeV

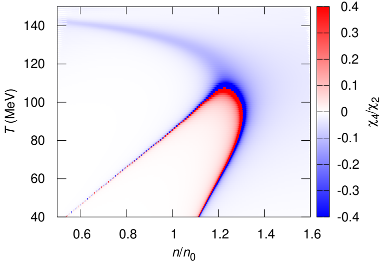
Summary and outlook

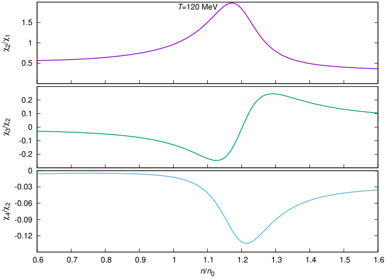
- Nonequilibrium chiral dynamics describes entropy production
- FOPT dynamics leads to significant increase in S/A
- Strong enhancement of π/p at onset of QCD phase transition
- Next: Dilepton production

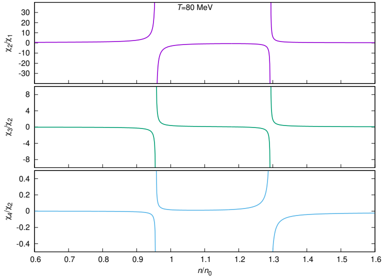


(Savchuk, Motornenko, Steinheimer et al., arXiv:2209.05267)

Susceptibilities near the critical point







- Phase diagram in T-n_q plane
- Spinodal instabilities at $T < T_{cp}$
- Diverging susceptibilities