Enhanced pion-to-proton ratio at a dynamical QCD phase transition

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with T. Bumnedpan, A. Limphirat, 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

NeD workshop 2022, Krabi

Nakhon Ratchasima

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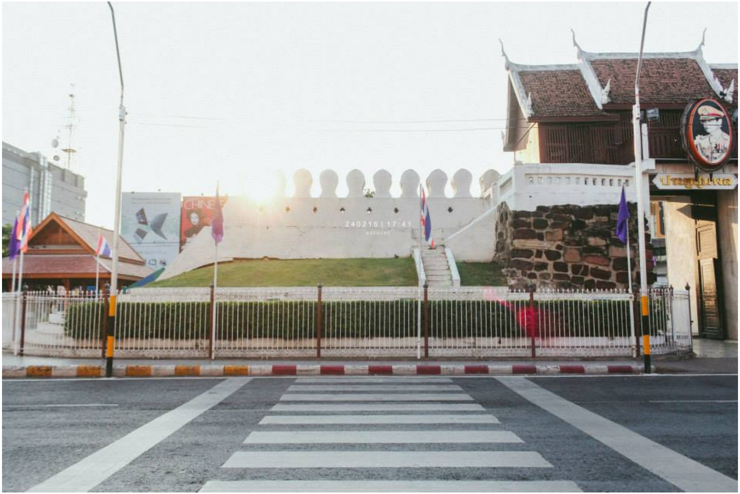

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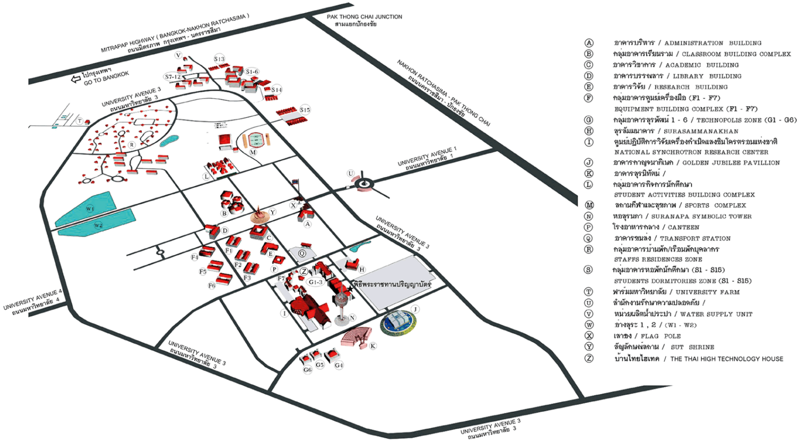

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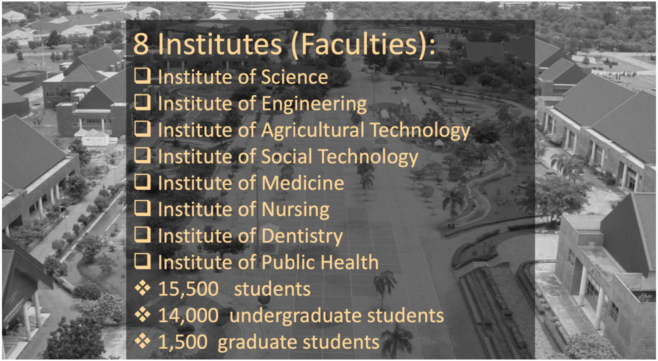

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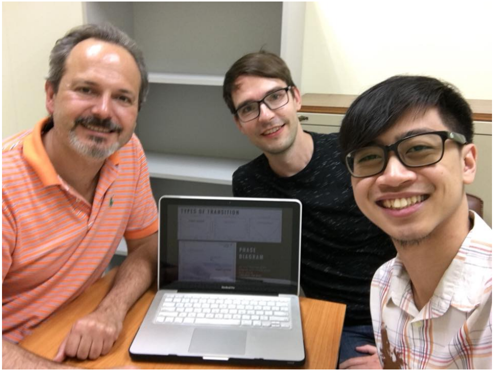

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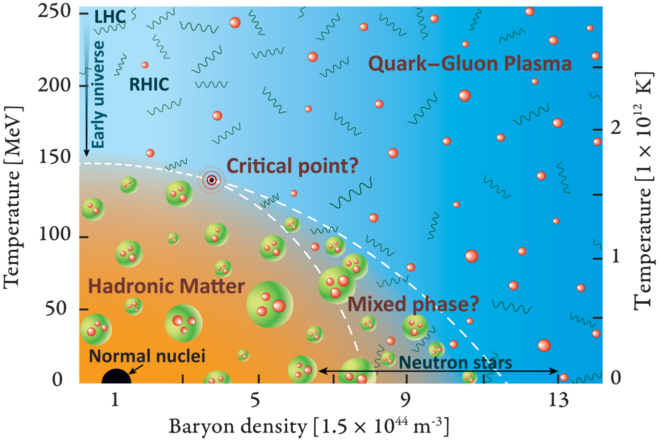
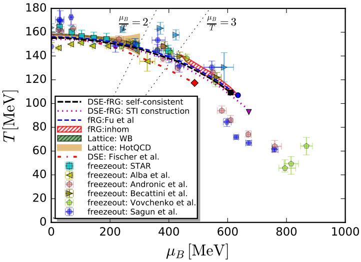
Outline

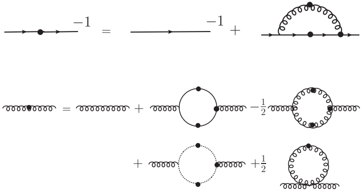
The QCD Phase Diagram



First principle calculations

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

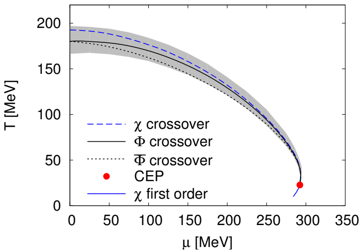




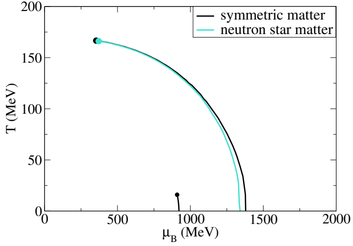
(Gao, Pawlowski, Phys. Lett. B **820**, 2021)

Effective Models

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



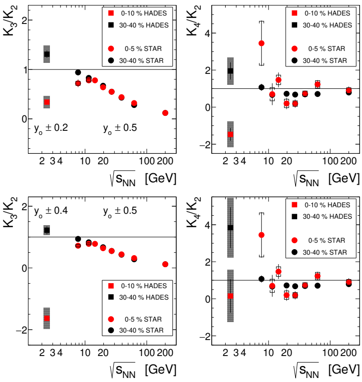
(Herbst, Pawlowski, Schaefer, Phys. Lett. B **696**, 2011)



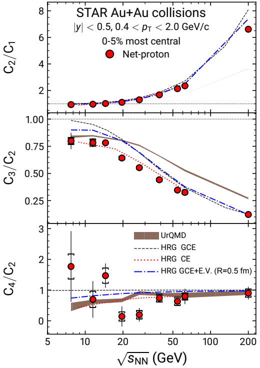
(Dexheimer, Schramm, Phys. Rev. C **81**, 2010)

Critical Point - Signals and Observables

1. Higher order cumulants: HADES and STAR data



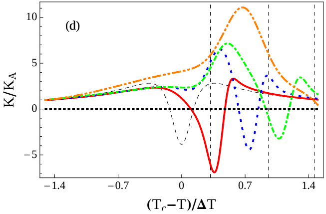
(HADES coll., Phys. Rev. C **102**, 2020)



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

Critical Point - Signals and Observables

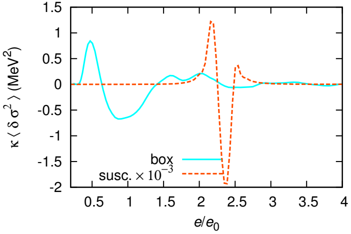
2. Nonequilibrium effects

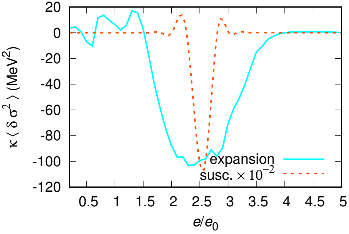


(Mukherjee, Venugopalan, Yin, Phys. Rev. C **92**, 2015)

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.

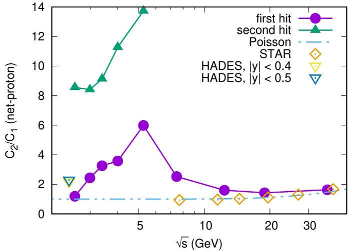
$$\delta N = \delta N^0 + V\, g\, \delta\sigma\, d \int \frac{\mathrm{d}^3 p}{(2\pi)^3} \frac{\partial n_p}{\partial m}$$

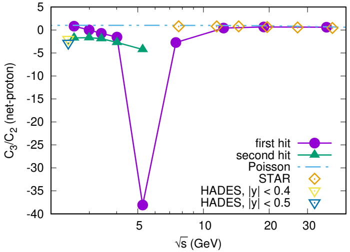
- Relate net-proton to sigma cumulants

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

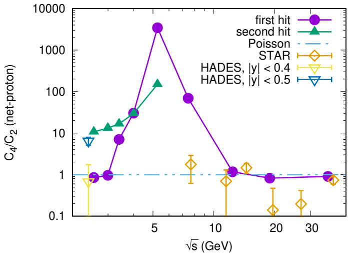
(Stephanov, Phys. Rev. Lett. **107**, 2011)

Critical Point - Signals and Observables





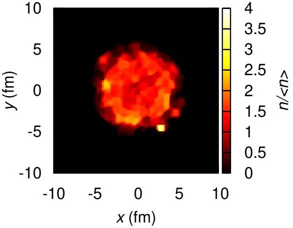
- Poisson baseline approached for large $\sqrt{s}$
- Strongly enhanced cumulants near spinodal line
- FOPT allows for wider range of cumulants

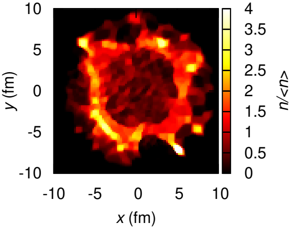


(CH, Saikham et al., Phys. Rev. C **106**, 2022)

First-order Phase Transition - Signals and Observables

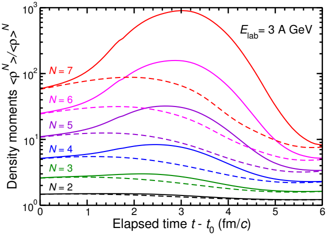
1. Nonequilibrium effects: Spinodal instabilities





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

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

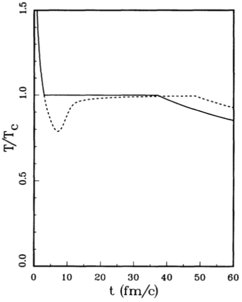


(Steinheimer, Randrup, Phys. Rev. Lett. **109**, 2012)

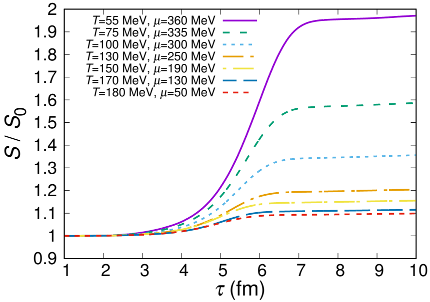
First-order Phase Transition - Signals and Observables

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)

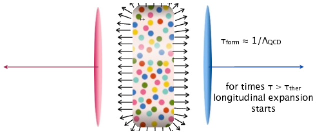


(CH, Kittiratpattana et al., Phys. Lett. B **790**, 2019)

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

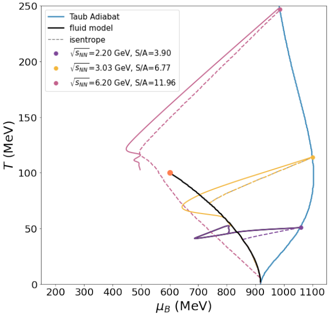
Initial Conditions

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

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

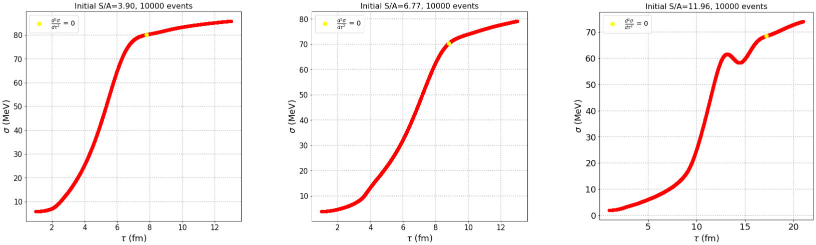
- Relate collision energy from compression:

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



(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

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

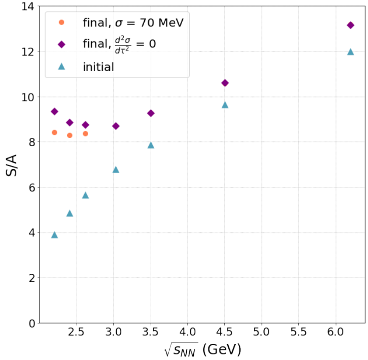
- Parameter set A:
  $a = 0.157$ GeV, $b = 0.087$ GeV^{-1} and $c = 0.092$ GeV^{-3}

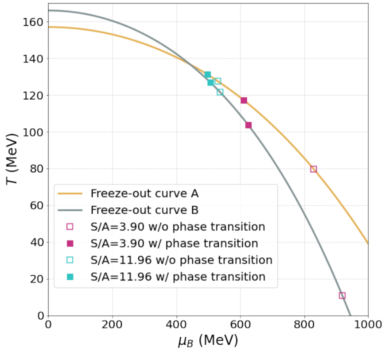
  (Vovchenko, Begun, Gorenstein, Phys. Rev. C **93**, 2016)

- 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



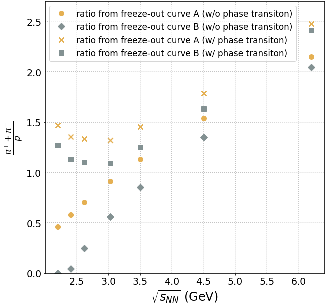


(Bumnedpan, CH, JS, MB, Phys. Lett. B **835**, 2022)

- 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

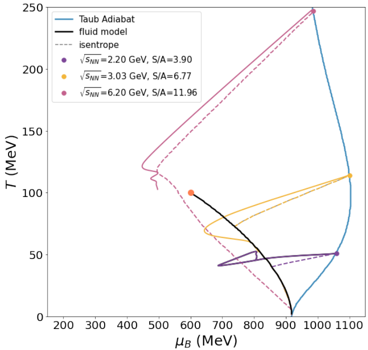


(Bumnedpan, CH, JS, MB, Phys. Lett. B **835**, 2022)

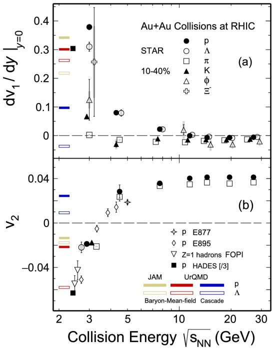
- Pion-to-proton ratio as observable for S/A
- FOPT scenario leads to increase at low $\sqrt{s}$
- In the model: Initial state always in restored phase
- Realistically: Jump in π/p at onset of chiral PT, around ~ 3 GeV

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

Caveats and what to look for



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

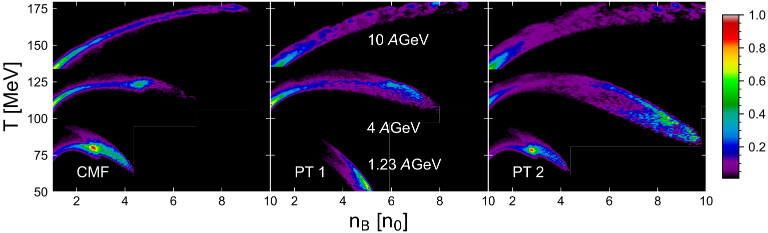


(STAR coll., Phys. Lett. B **827**, 2022)

- 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

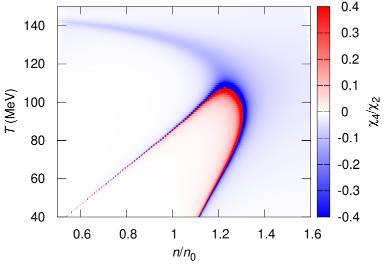
Summary and outlook

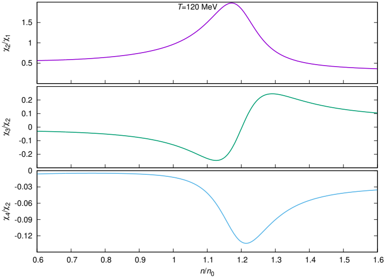
- Nonequilibrium chiral dynamics describes entropy production
- FOPT dynamics leads to significant increase in S/A
- Strong enhancement of π/p at onset of QCD phase transition
- Next: Dilepton production

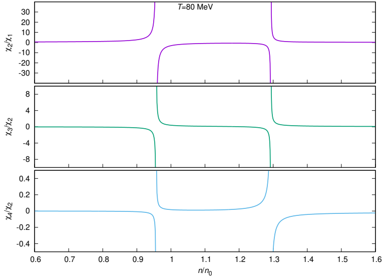


(Savchuk, Motornenko, Steinheimer et al., arXiv:2209.05267)

Susceptibilities near the critical point







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