Impact of resonance decays on critical fluctuation signals

M. Bluhm [1], M. Nahrgang [2] and T. Schäfer [1]

[1] Department of Physics, North Carolina State University, Raleigh, NC 27695, USA

[2] Department of Physics, Duke University, Durham, NC 27708, USA

E-mail: mbluhm@ncsu.edu

Introduction

Fluctuations of the conserved charges (B,Q,S) in QCD are sensitive to the nature of the relevant degrees of freedom. They provide unique means

- to explore the phase diagram of QCD matter,
- to locate prominent landmarks, e.g. the **C**ritical **P**oint or the 1st-order phase transition line.

Experimentally, moments of event-by-event multiplicity distributions are measured in the RHIC beam energy scan to learn about these fluctuations as functions of $\sqrt{s}$.

Critical fluctuations as signals for the CP can be associated with fluctuations in the order parameter, here the chiral field σ (more precisely a linear combination of σ and the net-baryon density n_B).

In this study, we focus on net-p fluctuations as measured at RHIC as a proxy for net-B fluctuations. The hadron resonance gas model in grand-canonical ensemble formulation provides a suitable baseline and allows us to incorporate the effect of resonance decays as stochastic processes.

Modeling critical fluctuations

The influence of the CP on multiplicity distributions can be studied phenomenologically by making a mean field ansatz for the interaction between particles and the critical mode adopted from linear-σ models (i.e. part of the hadron mass generation):

$$\mathcal{L}_{\rm int} = g_{i\sigma}\bar{\psi}_i\sigma\psi_i\,,$$

- fluctuations $\delta\sigma$ lead to fluctuations in the hadron masses $m_i \to m_i + g_{i\sigma}\delta\sigma$,
- affects fluctuations in the distribution functions (statistical + critical):

$$\delta f_i = \delta f_i^0 + g_{i\sigma}\frac{\partial f_i^0}{\partial m_i}\delta\sigma\,.$$

This introduces correlations among p and $\bar{p}$. Assuming an independence of purely statistical and critical fluctuations, the impact on (for example) the 2nd-order cumulant is

$$C_2^{\text{net-p}} = \langle(\Delta N_p)^2\rangle + \langle(\Delta N_{\bar{p}})^2\rangle - 2\langle\Delta N_p\,\Delta N_{\bar{p}}\rangle$$

with

$$\langle(\Delta N_i)^2\rangle = \langle(\Delta N_i^0)^2\rangle + \langle(V\delta\sigma)^2\rangle I_i^2$$
$$\langle\Delta N_i\,\Delta N_{\bar{i}}\rangle = \langle(V\delta\sigma)^2\rangle I_i I_{\bar{i}}$$

and

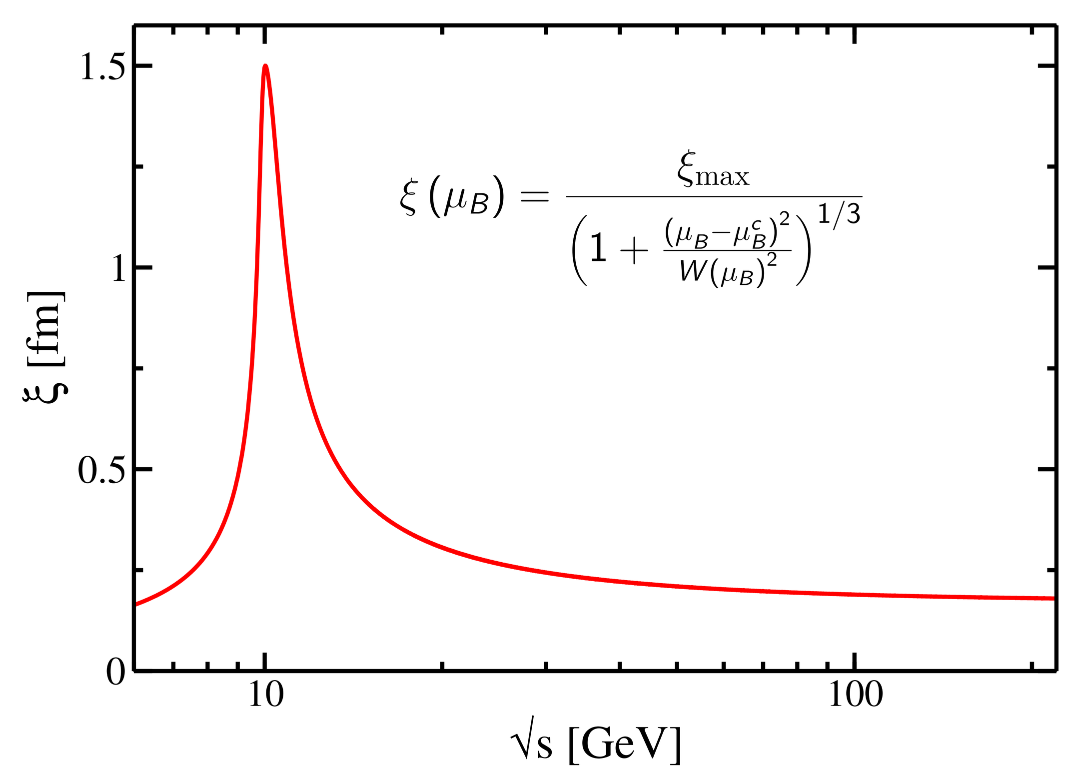
$$I_i = \frac{g_{i\sigma}d_i}{T}\int_k f_i^0(k)(1-f_i^0(k))/\gamma_i(k)\,,$$

$\gamma_i(k) = (k^2+m_i^2)^{1/2}$, $g_{p\sigma} = 5$ and $\langle(V\delta\sigma)^2\rangle = VT\xi^2$, cf. [1].

For a quantitative analysis, the values of the correlation length ξ at chemical freeze-out (FO) must be known:

- at a CP $\xi \to \infty$ in thermodynamic equilibrium,
- in heavy-ion collisions the growth of ξ is limited by the size and the dynamics of the system (critical slowing down, proximity of the chemical FO to the CP)

A model for the $\sqrt{s}$-dependence of ξ for a given μ_B at chemical FO was proposed in [2]. This ansatz respects that the CP belongs to the static universality class of the 3d-Ising model. An example of $\xi(\sqrt{s})$ for $\xi_{\rm max} = 1.5$ fm, $\mu_B^c = 350$ MeV with an estimated size of 50 MeV for the critical region is shown in the figure below.



Inclusion of resonance decays

Resonance decays contribute significantly to the multiplicity distributions. In order to include baryonic resonance decays in the presence of the critical mode as a source of stochastic fluctuations in net-p, we make an ansatz for the coupling of a resonance R to the σ-field as

$$g_{R\sigma} = \frac{m_R}{m_p}(3-|S_R|)\,\frac{g_{p\sigma}}{3}\,.$$

This ansatz, which induces correlations between R and $\bar{R}$, assumes that resonances with non-vanishing strangeness content couple less strongly to σ. The impact on the 2nd-order cumulant is

$$\begin{aligned}\hat{C}_2^{\text{net-p}} &= \langle(\Delta N_p)^2\rangle + \langle(\Delta N_{\bar{p}})^2\rangle - 2\langle\Delta N_p\,\Delta N_{\bar{p}}\rangle \\ &+\sum_R\langle N_R\rangle\left(\langle\Delta n_p^2\rangle_R + \langle\Delta n_{\bar{p}}^2\rangle_R\right) \\ &+\sum_R\langle(\Delta N_R)^2\rangle\left(\langle n_p\rangle_R^2 + \langle n_{\bar{p}}\rangle_R^2\right) \\ &-2\sum_R\langle\Delta N_R\,\Delta N_{\bar{R}}\rangle\langle n_p\rangle_R\langle n_{\bar{p}}\rangle_R\,,\end{aligned}$$

where $\langle n_i\rangle_R = \sum_r b_r^R n_{i,r}^R$ and $\langle\Delta n_i\,\Delta n_j\rangle_R = \sum_r b_r^R n_{i,r}^R n_{j,r}^R - \langle n_i\rangle_R\langle n_j\rangle_R$.

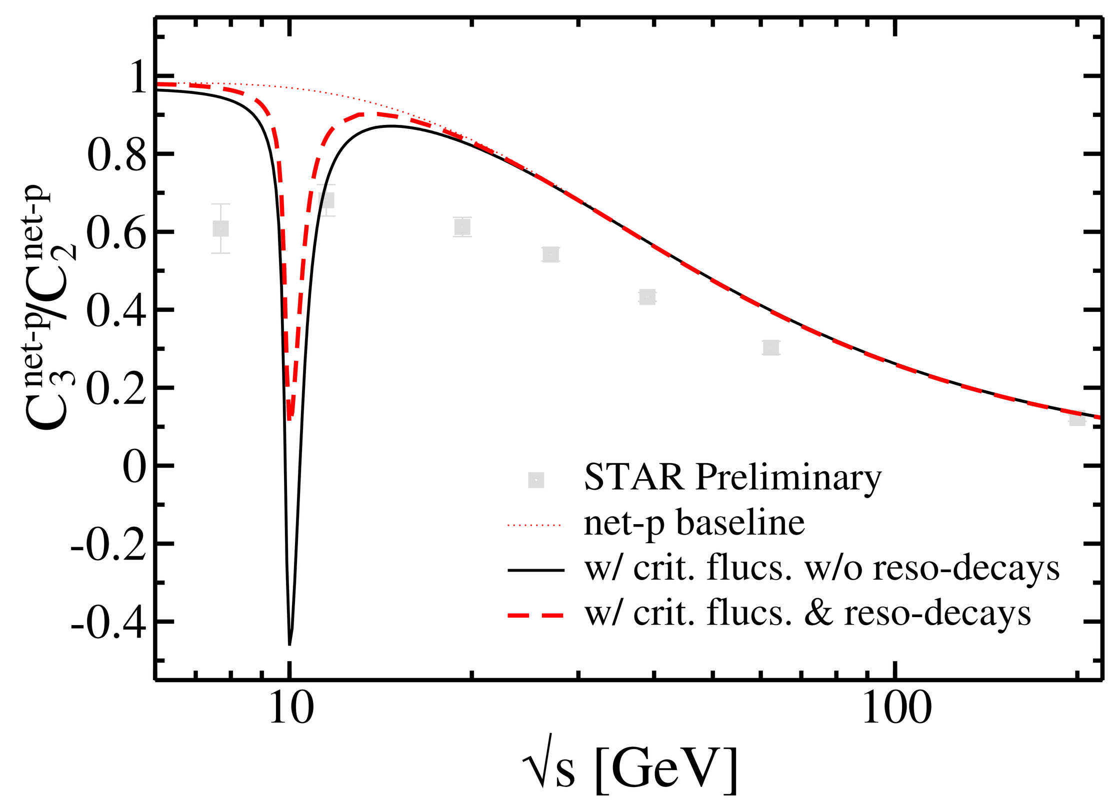
Results

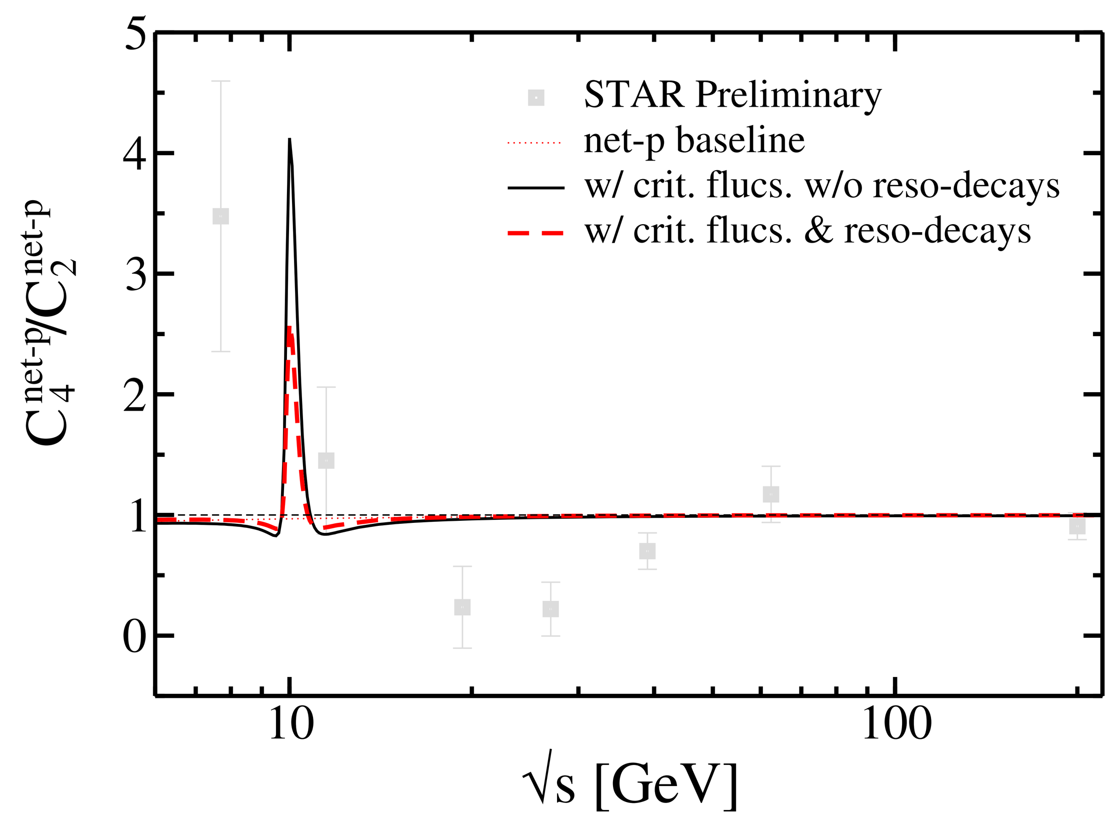
We show the results of $C_3^{\text{net-p}}/C_2^{\text{net-p}}$ and $C_4^{\text{net-p}}/C_2^{\text{net-p}}$ for the given $\xi(\sqrt{s})$ with and without resonance decays. The higher-order cumulants involve higher-order fluctuations of the σ-field [1]

$$\langle(V\delta\sigma)^3\rangle = 2VT^{3/2}\,\widetilde{\lambda}_3\,\xi^{9/2}\,,$$
$$\langle(V\delta\sigma)^4\rangle_c = 6VT^2\,(2\widetilde{\lambda}_3^2-\widetilde{\lambda}_4)\,\xi^7\,.$$

We include in each cumulant the statistical and the most critical (with the strongest dependence on ξ) fluctuation contributions. The universal parameters are fixed to $\widetilde{\lambda}_3 = 4$ and $\widetilde{\lambda}_4 = 12$.

We observe that while critical fluctuations lead to pronounced deviations from the purely statistical baseline results, resonance decays reduce the critical fluctuation signals significantly - but not completely.





Conclusions and outlook

Critical fluctuation signals are reduced but survive when resonance decays are included.

For a more realistic treatment certain refinements are necessary:

- the parameters $\widetilde{\lambda}_3$ and $\widetilde{\lambda}_4$ should depend on the direction the CP is approached and its proximity to the chemical FO,
- other late stage effects such as isospin randomization [3,4] should be considered,
- at large n_B repulsive interactions among hadrons might be relevant.

References

[1] M.A. Stephanov, PRL **102** (2009).

[2] C. Athanasiou et al., PRD **82** (2010).

[3] M. Kitazawa and M. Asakawa, PRC **86** (2012).

[4] M. Nahrgang et al., arXiv:1402.1238.