Chiral criticality and repulsive interactions in hot hadronic matter

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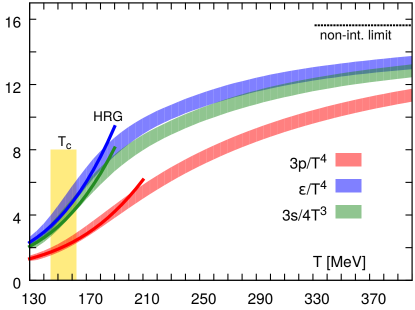
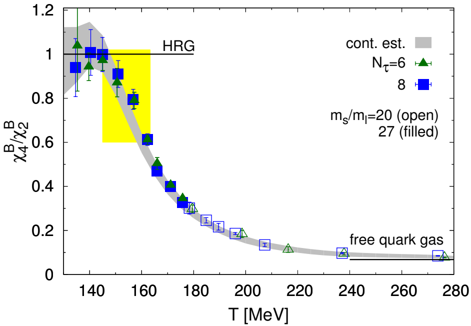
Hadron Resonance Gas vs Lattice QCD



HotQCD, PRD (2014)

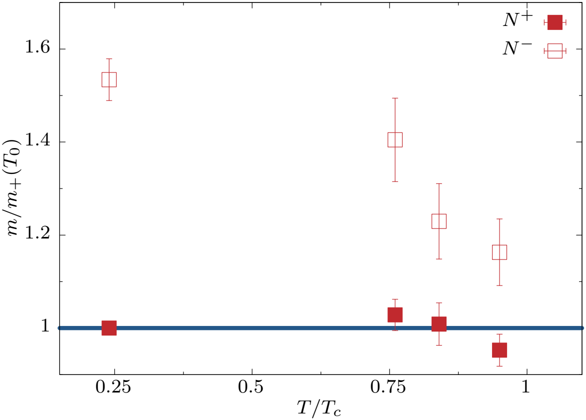


HotQCD, PRD (2017)

- Pressure in the HRG: $P^{\mathrm{HRG}}(T,\mu_B,\mu_S,\mu_Q) = \sum_{\mathrm{i\in had}} P^{\mathrm{ideal}}(T,\mu_i;m_i)$
- HRG describes well LQCD equation of state and some fluctuation observables up to $\simeq T_c$
- Rapid breakdown around T_c in kurtosis $\rightarrow$ changeover to QGP

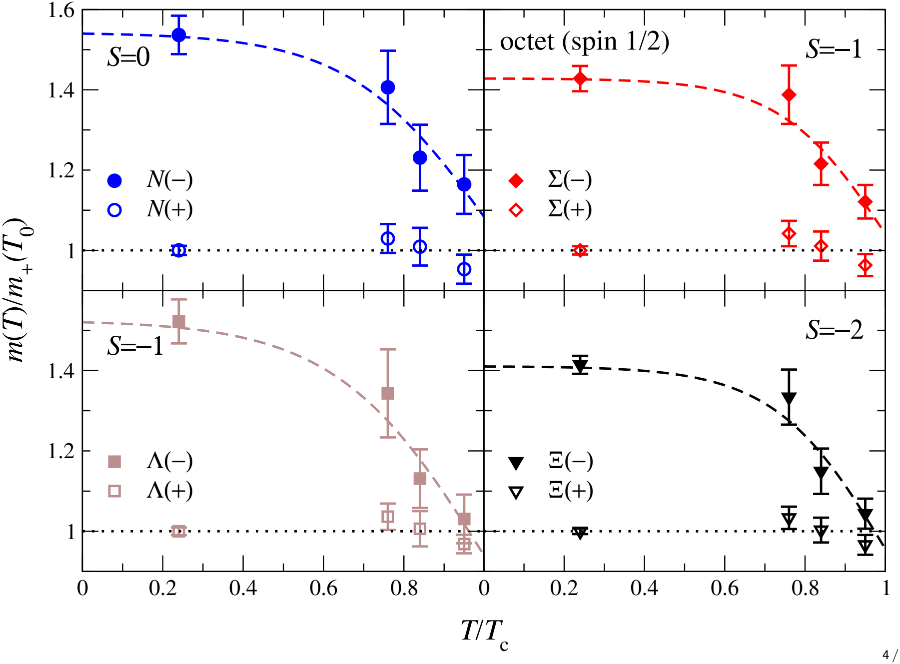
Parity Doubling in Lattice QCD

Aarts *et al*, JHEP **1706**, 034 (2017)

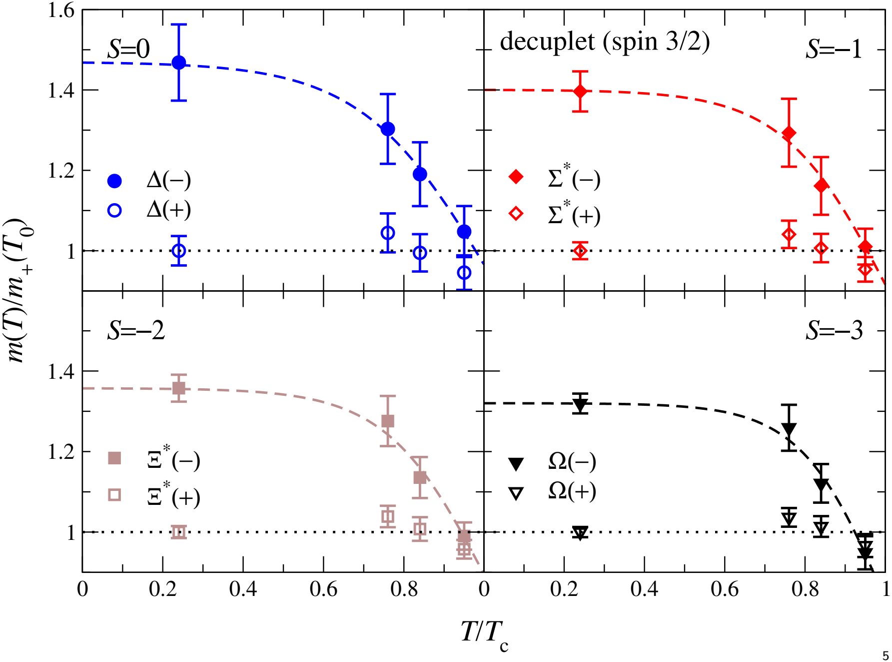


- imprint of chiral symmetry restoration in the baryonic sector
- general tendency: N^+ - constant; N^- - dramatic drop of mass toward chiral crossover
- chiral partners $N^\pm$ stay massive around T_c
- in-medium effects $\rightarrow$ mass shifts $\rightarrow$ input for HRG

Parity Doubling for Light Baryons Aarts *et al*, PRD **99** (2019)



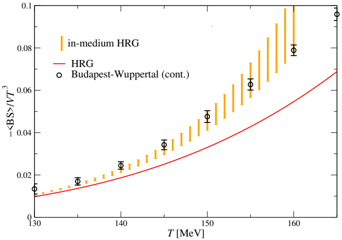
Parity Doubling for Light Baryons Aarts *et al*, PRD **99** (2019)



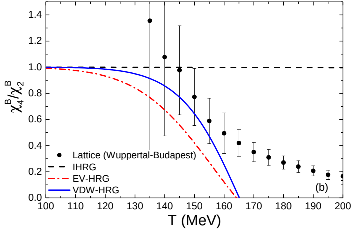
In-medium Hadron Resonance Gas vs Lattice QCD

- parity doubling improves the agreement of HRG with LQCD Aarts et al. (2018)
- agreement is only accidental with only mass shifts in HRG Morita et al. (2018)

- excluded volume and van der Waals HRG improve the agreement with LQCD
- deviations from HRG baseline → repulsive hadron intractions Vovchenko et al. (2017)



Aarts et al. (2018)



Vovchenko et al. (2017)

To what extent the behavior is dominated by the chiral criticality and repulsive interactions?

What are the origins of the structures present in higher-order cumulants?

Delineating in-medium effects in higher-order cumulants in $\sigma - \omega$ model

- Cumulants of the net-baryon number: $\chi_n = T^{n-4} \left. \frac{\partial^{n-1} n_B}{\partial \mu_B^{n-1}} \right|_T$

- In the mean-field approx.: $n_B = n_B(T, \mu_B, \sigma(T, \mu_B), \omega(T, \mu_B))$

- General structure of the second-order cumulant:

$$\chi_2 = \chi_2^{\mathrm{id}} \beta_{\mathrm{rep}} + \frac{\partial n_B}{\partial \sigma} \frac{\partial \sigma}{\partial \mu_B} \qquad \xrightarrow{\mu_B = 0} \qquad \chi_2^{\mathrm{id}} \beta_{\mathrm{rep}}$$

attractive repulsive

- At $\mu_B = 0 \rightarrow \chi_2^{\mathrm{id}}(T, \sigma)$ - HRG with in-medium masses due to chiral restoration (σHRG)

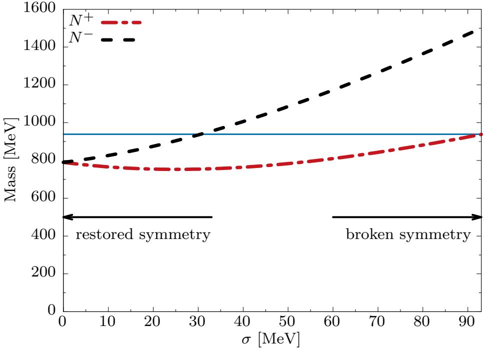
- $\beta_{\mathrm{rep}} = 1 - g_\omega \frac{\partial \omega}{\partial \mu_B}$ - suppression factor due to repulsive interactions

- Approximations for higher orders and ratios:

$$\chi_n \approx \chi_n^{\mathrm{id}} \beta_{\mathrm{rep}}^{n-1} + \ldots \qquad \frac{\chi_n}{\chi_m} \approx \frac{\chi_n^{\mathrm{id}}}{\chi_m^{\mathrm{id}}} \beta_{\mathrm{rep}}^{n-m} + \ldots$$

Parity Doubling in SU(2) Chiral Models DeTar, Kunihiro PRD **39** (1989)

$$m_\pm = \sqrt{m_0^2 + c_1^2\sigma^2} \mp c_2\sigma \quad \xrightarrow{\sigma\to 0} \quad m_0$$



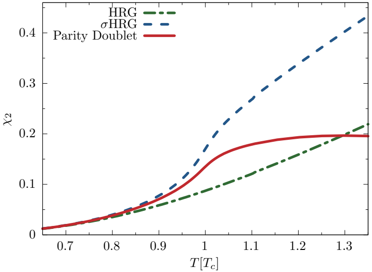
$\longleftarrow$ $N(1535)$

$\longleftarrow$ $N(939)$

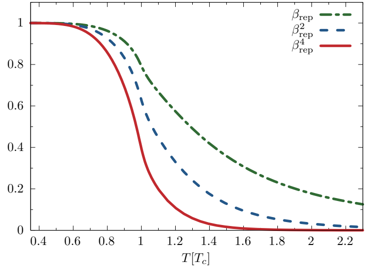
- chiral symmetry restoration $\to$ exchange of σ meson
- repulsive interactions $\to$ exchange of ω meson
- mean field approximation for chiral criticality
- thermodynamic potential: $\Omega = \sum_{x=\pm} \Omega_\pm + V_\sigma + V_\omega$

Second-order cumulant

- HRG - non-critical baseline
- HRG $\xrightarrow{+chiral}$ σHRG $\xrightarrow{+repulsion}$ Parity Doublet
- qualitative differences in χ_2 $\rightarrow$ repulsive interactions



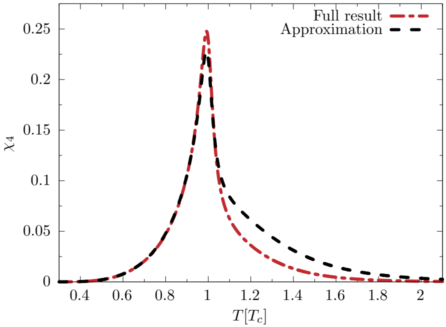
$$\chi_2 = \chi_2^{\mathrm{id}} \beta_{\mathrm{rep}}$$

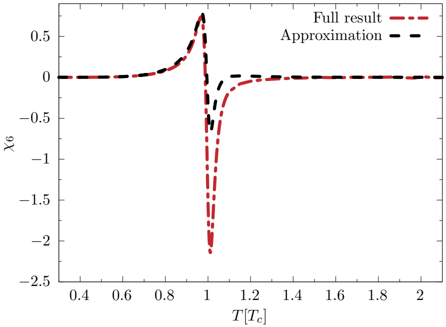


- repulsion becomes more important with increasing temperature
- at T_c: $\beta_{\mathrm{rep}} \simeq 0.8 \rightarrow \chi_2$ reduced by 20%
- repulsion more readily exposed in higher-order cumulants: $\chi_n \sim \beta_{\mathrm{rep}}^{n-1}$
- estimated suppresion of χ_4 and χ_6 is 41% and 67%, respectively

Approximations for higher-order cumulants

$$\chi_n \approx \chi_n^{\mathrm{id}} \beta_{\mathrm{rep}}^{n-1} + \dots$$

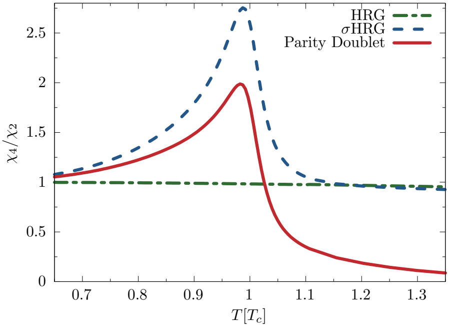


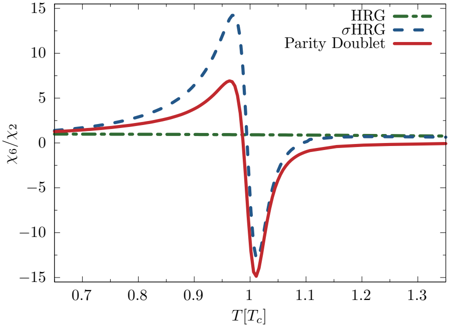


- $\chi_2 = \chi_2^{\mathrm{id}} \beta_{\mathrm{rep}}$ is exact $\rightarrow$ errors in ratios come from χ_4 and χ_6
- reasonable agreement up to $\sim 1.1\ T_c$
- qualitative structure is preserved

Ratios of higher-order cumulants: (hyper) kurtosis

interactions → strong deviations from the HRG baseline

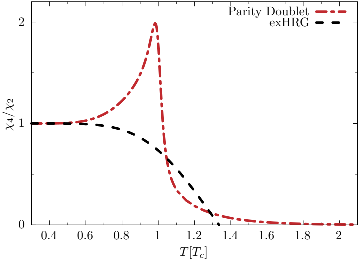


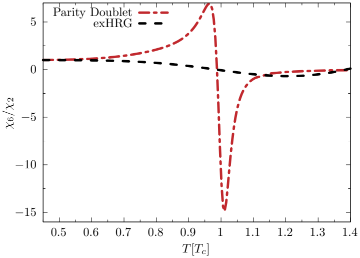


- structure dictated by chiral symmetry
- no chiral-critical behavior encoded in β

- χ_4/χ_2 and χ_6/χ_2 suppressed by repulsion, but qualitative structure the same

Comparison with excluded volume HRG





Excluded Volume HRG

$$P^{\mathrm{ev}}(T,\mu) = P^{\mathrm{id}}(T, \mu - v_0 P^{\mathrm{ev}}(T,\mu))$$

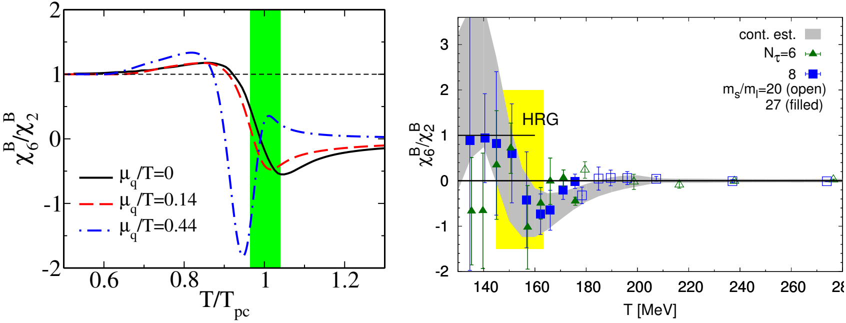
Fluctuations no longer skellam:

kurtosis $\dfrac{\chi_4^{\mathrm{ev}}}{\chi_2^{\mathrm{ev}}} \simeq 1 - 12 v_0 \phi(T)$

hyperkurtosis $\dfrac{\chi_6^{\mathrm{ev}}}{\chi_2^{\mathrm{ev}}} \simeq 1 - 60 v_0 \phi(T)$

- qualitatively different structure of the ratios
- χ_4/χ_2 - reduced from Skellam as seen in LQCD
- χ_6/χ_2 - fails to capture the characteristic properties

Comparison with excluded volume HRG



- structure persists when mesonic fluctuations are included, e.g., in FRG and LQCD

Friman et al (2011); Borsanyi et al (2018); Bazavov et al (2020)

repulsive interactions are insufficient

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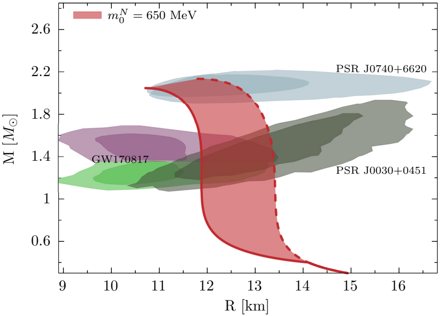
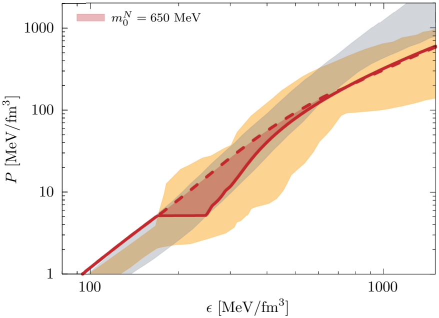
consistent framework with chiral effects and repulsive interactions needed

Astrophysical applications of parity doublet model





Properties of the EoS that is required to explain modern multi-messenger astronomy constraints, can be fully linked to the dynamical restoration of chiral symmetry.

$\downarrow$

conclusion about the existence of the quark matter in the stellar core may still be premature

MM, K. Redlich, C. Sasaki, arXiv:2110.11056

Conclusions

Interplay between chiral dynamics and repulsive interactions at $\mu_B = 0$:

- higher-order cumulants are sensitive to hadronic interactions
- factorization of $\chi_2 \longrightarrow$ (attractive) $\times$ (repulsive)
  - approximation for higher orders
- repulsive interactions become readily exposed in the structure of the higher-order cumulants
- excluded volume model fails to reproduce dominant chiral critical behavior
- consistent framework with chiral effects and repulsive interactions needed.

Thank You