Fluctuations near the liquid-gas and chiral phase transitions

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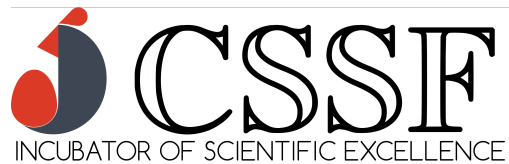
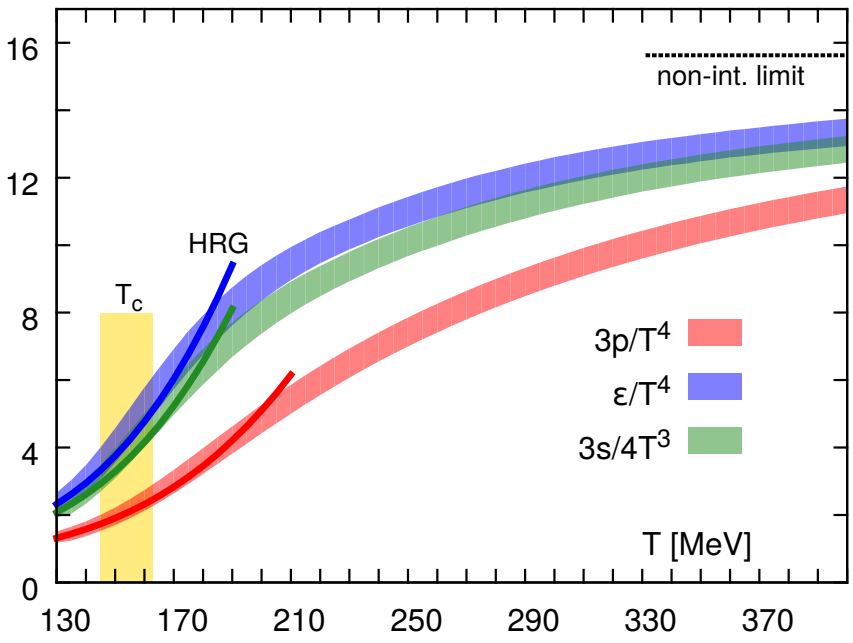
MM, K. Redlich, C. Sasaki, Phys.Rev.D 103 (2021) 5, 054035
MM, K. Redlich, C. Sasaki, Phys.Rev.D 107 (2023) 5, 054046

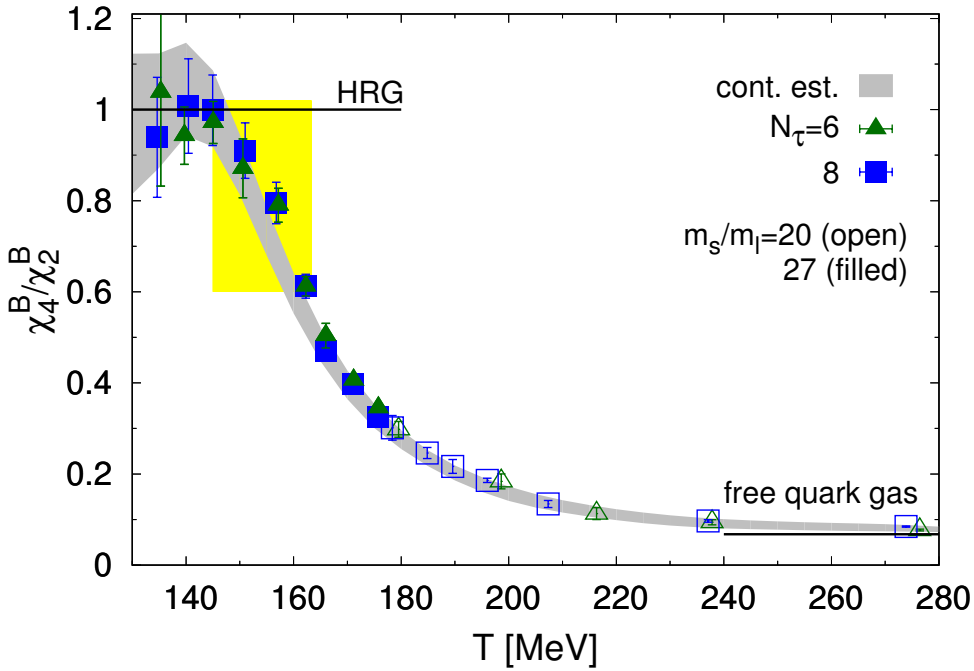
Exploring Quark-Gluon Plasma through soft and hard probes
Belgrade, 30.05.2023



Hadron Resonance Gas vs Lattice QCD



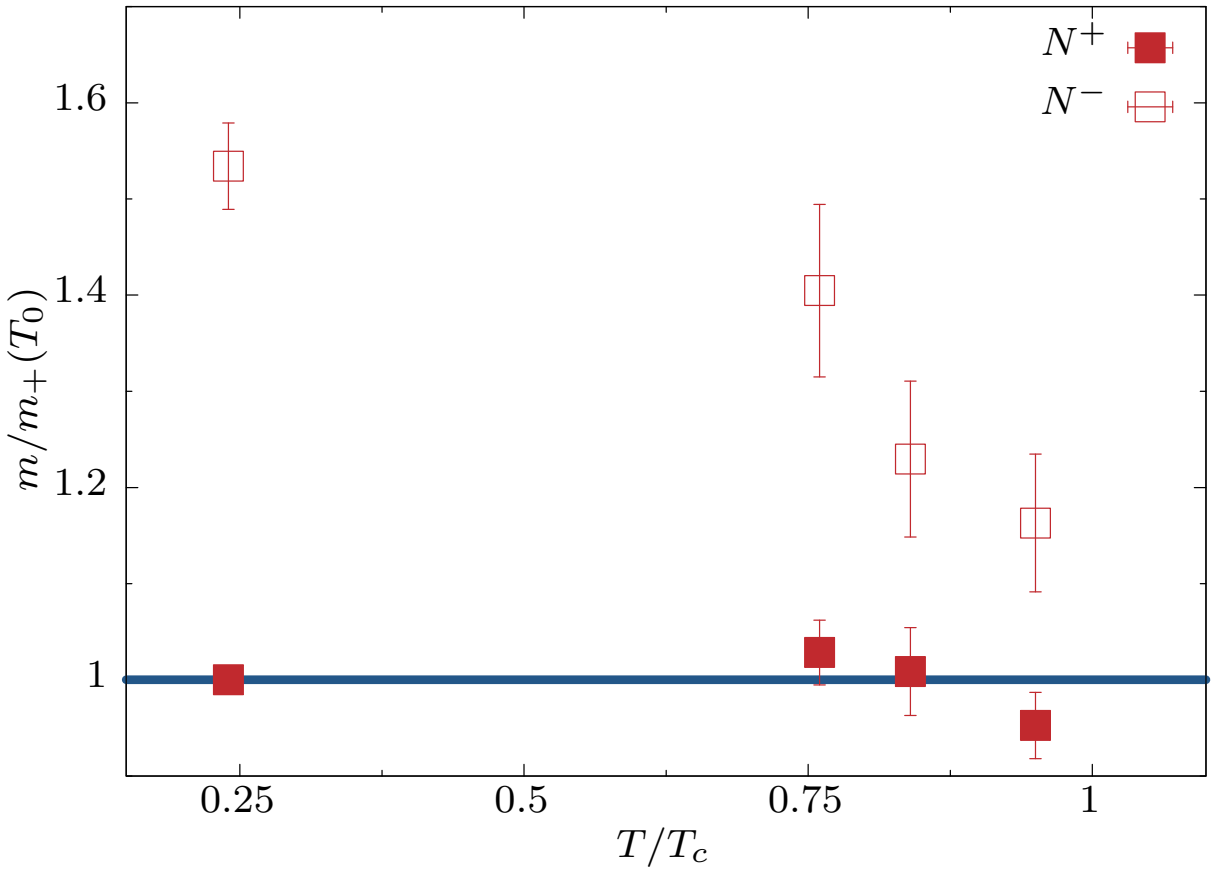
HotQCD, PRD (2014)



HotQCD, PRD (2017)

- Pressure in the HRG: $P^{\mathrm{HRG}}(T,\mu_B,\mu_S,\mu_Q) = \sum_{i\in \mathrm{had}} P^{\mathrm{ideal}}(T,\mu_i;m_i)$
- HRG describes well LQCD equation of state and some fluctuations up to $\simeq T_c$
- Taylor expansion of LQCD Pressure: $P = \sum_{k=0}^{\infty} \left(\frac{\mu_B}{T}\right)^k \frac{\chi_k^B}{k!}$, where $\chi_k^B = \frac{\partial^k P}{\partial(\mu_B/T)^k}$
- Kurtosis: $\frac{\chi_4^B}{\chi_2^B} \sim B^2$: breakdown around $T_c \rightarrow$ changeover to QGP

Parity Doubling in Lattice QCD Aarts *et al*, JHEP **1706**, 034 (2017)

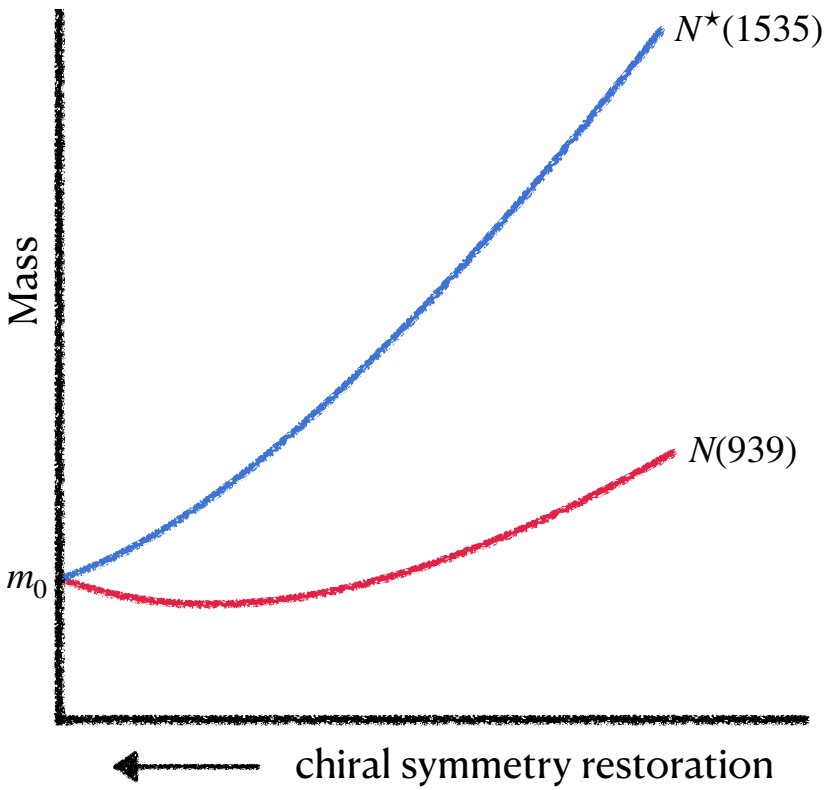


- imprint of chiral symmetry restoration in the baryonic sector
- general tendency: N^+ - const; N^- - dramatic drop toward chiral crossover
- chiral partners $N^\pm$ stay massive around T_c

Parity Doubling in SU(2) Chiral Models: Parity Doublet Model

Model a'la DeTar, Kunihiro PRD **39** (1989) $\longrightarrow \mathcal{L}_{\rm mass} = m_0(\bar{\psi}_1\gamma_5\psi_2 - \psi_2\gamma_5\psi_1)$

$$M_\pm = \sqrt{4m_0^2 + \alpha^2\sigma^2} \mp \beta\sigma \quad \xrightarrow{\sigma\to 0} \quad m_0$$



Chiral symmetry restoratio

$\downarrow$

$$M_- - M_+ = \beta\sigma$$

- Repulsive interactions $\longrightarrow$ exchange of ω
- Mean field approximation for chiral criticality

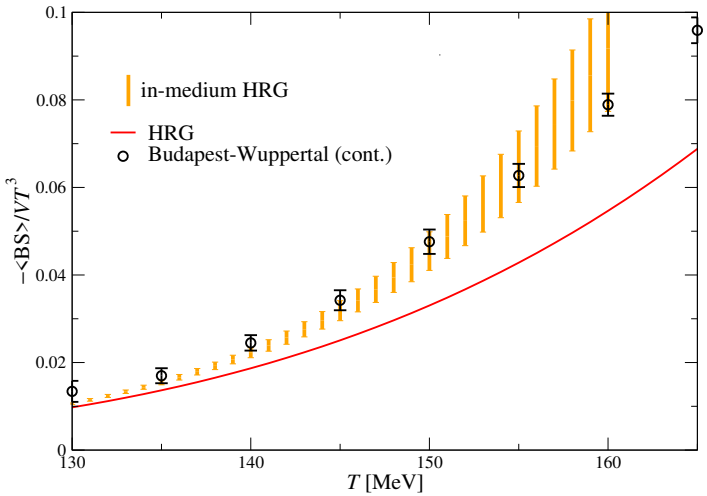
In-medium Hadron Resonance Gas vs Lattice QCD

- parity doubling $\longrightarrow$ agreement with LQCD

  Aarts *et al* (2018)

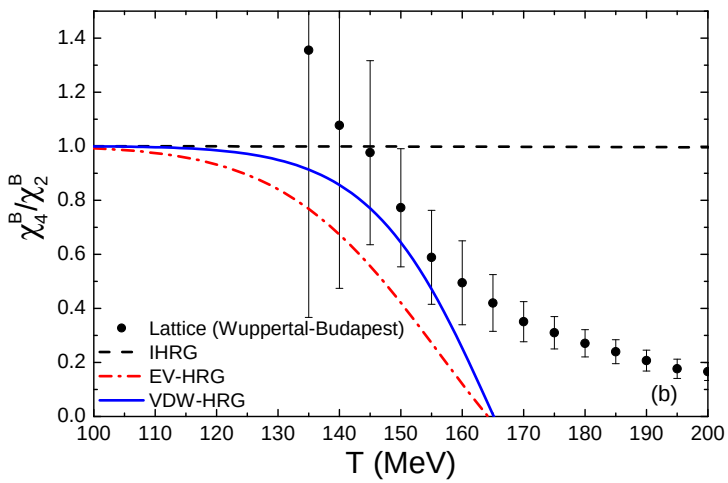
- mass shift $\longrightarrow$ agreement is accidental

  Morita *et al* (2018)



- excluded volume $\longrightarrow$ agreement with LQCD
- deviations from HRG $\longrightarrow$ repulsive int.

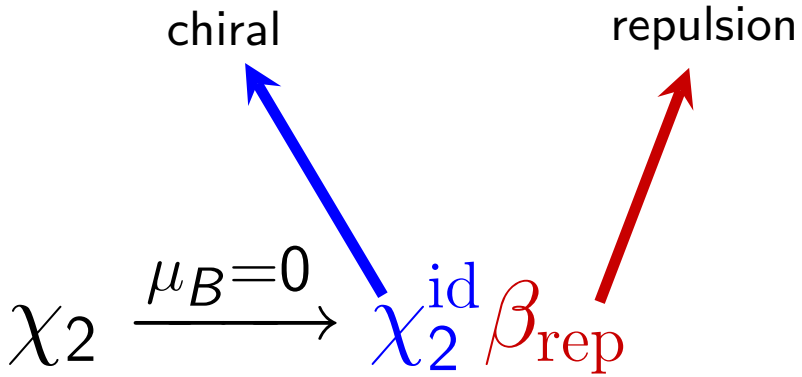
  Vovchenko *et al* (2017)

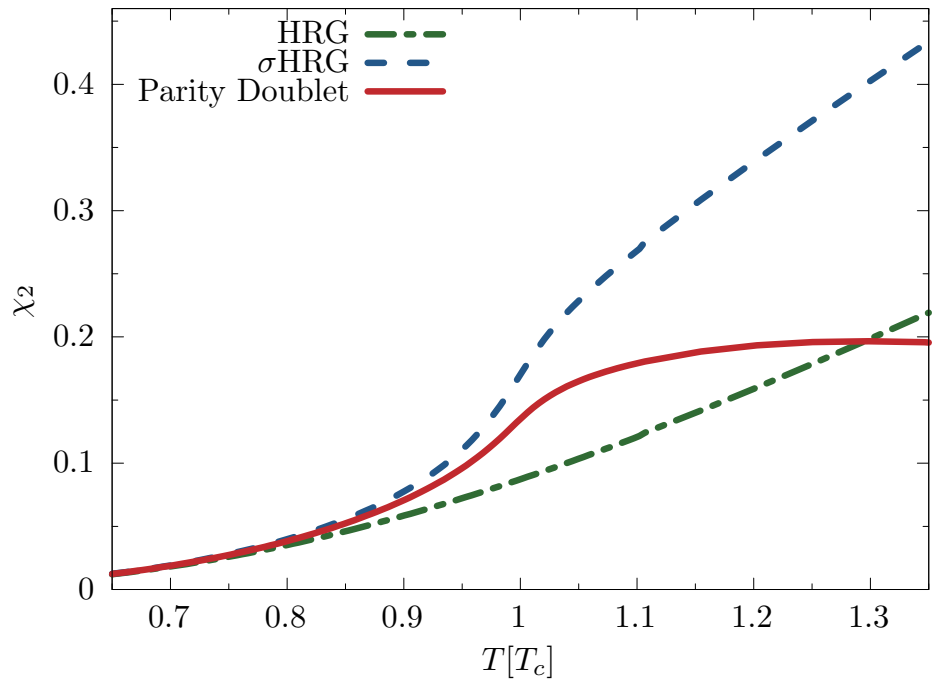


To what extent the behavior is due to chiral criticality and repulsive interactions?

Fluctuations and In-medium Effects in $\sigma - \omega$ Models

Susceptibility of the net-baryon number: $\chi_n = T^{n-4} \left. \frac{\partial^{n-1} n_B(T, \mu_B, \sigma, \omega)}{\partial \mu_B^{n-1}} \right|_T$

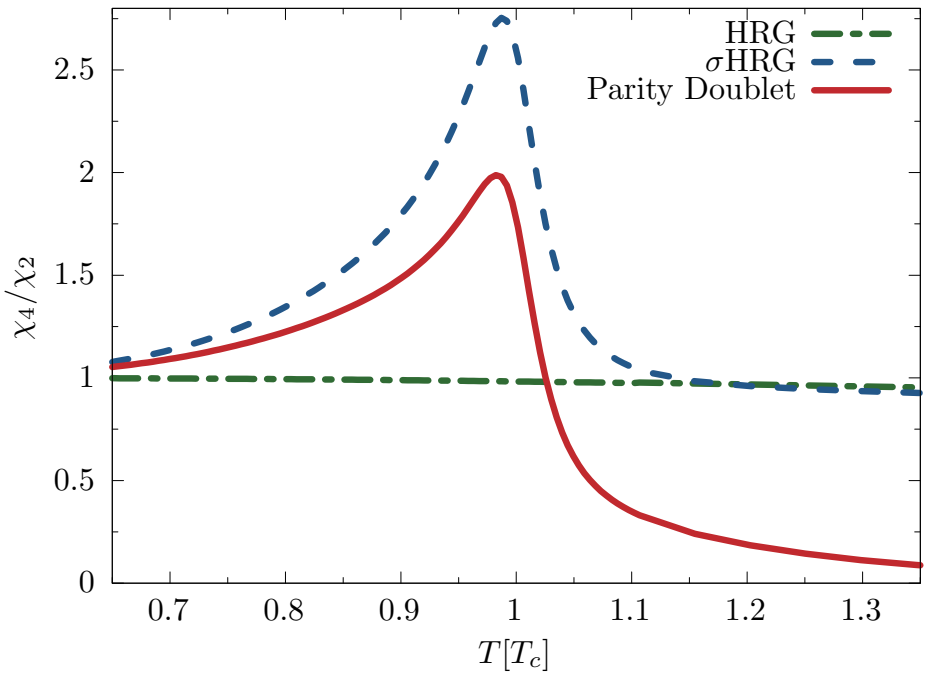




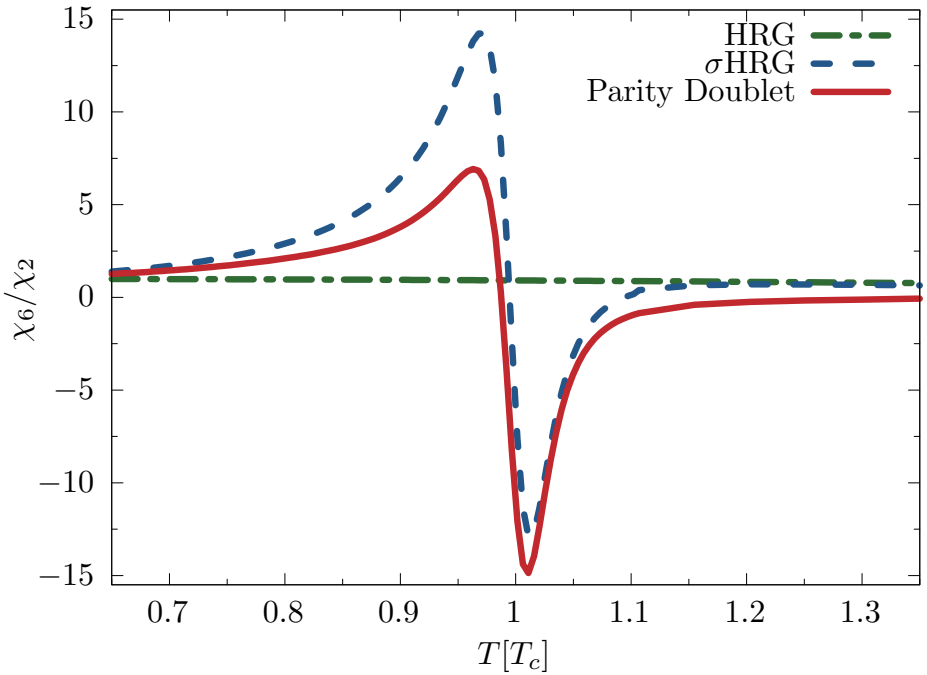
- HRG - non-critical baseline
- HRG $\xrightarrow{+\textit{chiral}}$ σHRG $\xrightarrow{+\textit{repulsion}}$ Parity Doublet
- Qualitative differences in $\chi_2 \rightarrow$ repulsive interactions: $\chi_2 = \chi_2^{\mathrm{id}} \beta_{\mathrm{rep}}$

Ratios of higher-order cumulants: (hyper) kurtosis

interactions $\longrightarrow$ strong deviations from the HRG baseline in $\frac{\chi_4}{\chi_2}$ and $\frac{\chi_6}{\chi_2}$

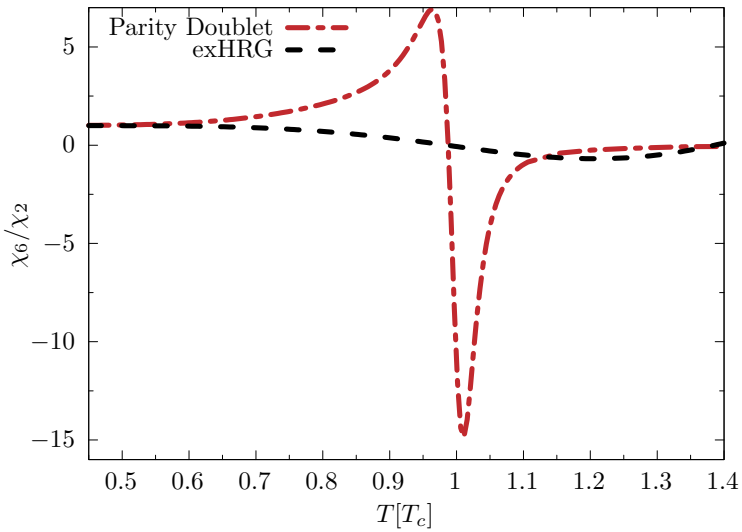


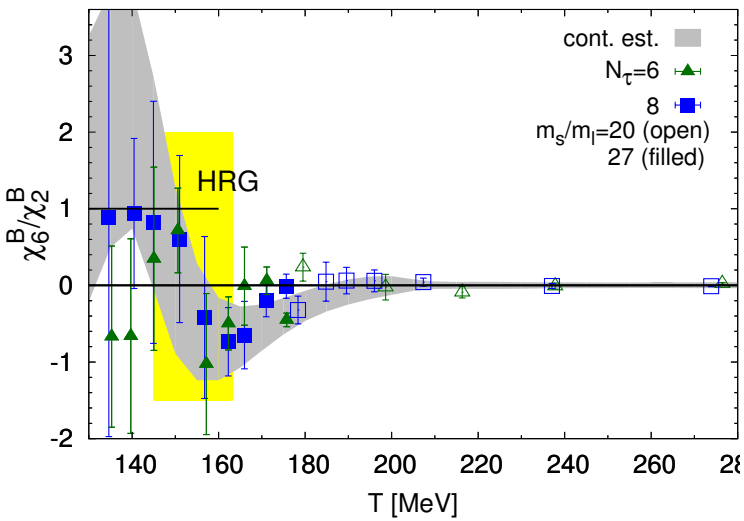
- structure dictated by chiral symmetry
- no chiral-critical behavior encoded in β



- 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

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

Fluctuations no longer skellam:

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

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

- qualitatively different structure of the ratios
- χ_6/χ_2 - fails to capture the characteristic properties

compare with Borsanyi et al (2018); Bazavov et al (2020)

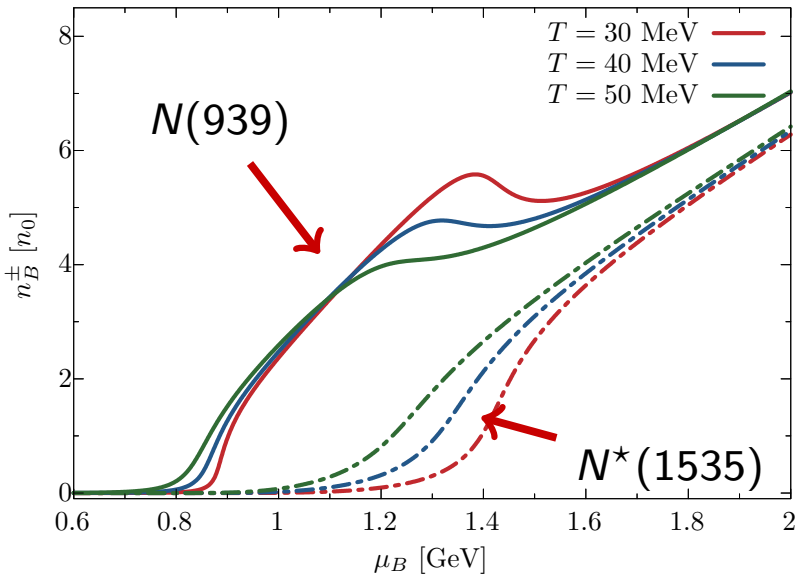
consistent framework with chiral effects and repulsive interactions needed

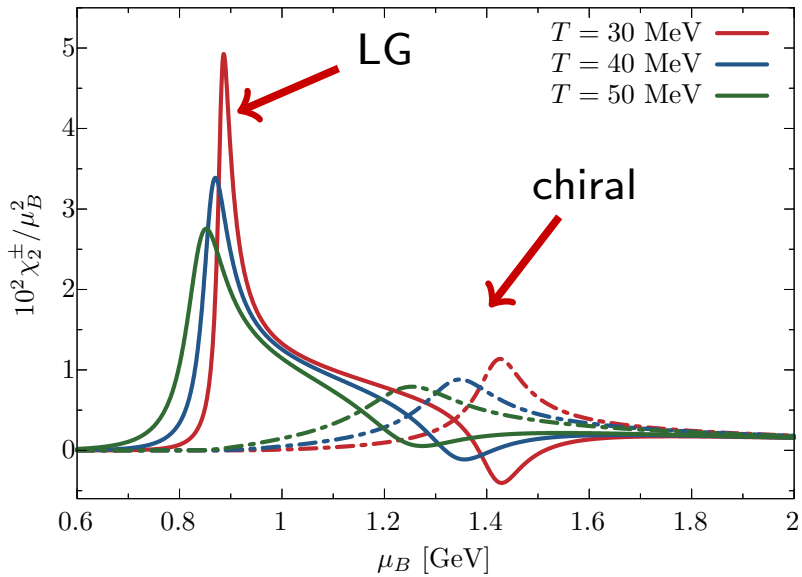
Fluctuations of Chiral Partners at Finite Density

$N(939)$ $N^\star(1535)$

$n_B = n_B^+ + n_B^-$ $\chi_2 = \chi_2^+ + \chi_2^-$

$$\chi_2^\pm = \left.\frac{\partial n_B^\pm}{\partial \mu_B}\right|_T = \frac{\partial n_B^\pm}{\partial \mu_B} + \frac{\partial n_B^\pm}{\partial m_\pm}\frac{\partial m_\pm}{\partial \sigma}\frac{\partial \sigma}{\partial \mu_B} + \frac{\partial n_B^\pm}{\partial \omega}\frac{\partial \omega}{\partial \mu_B}$$

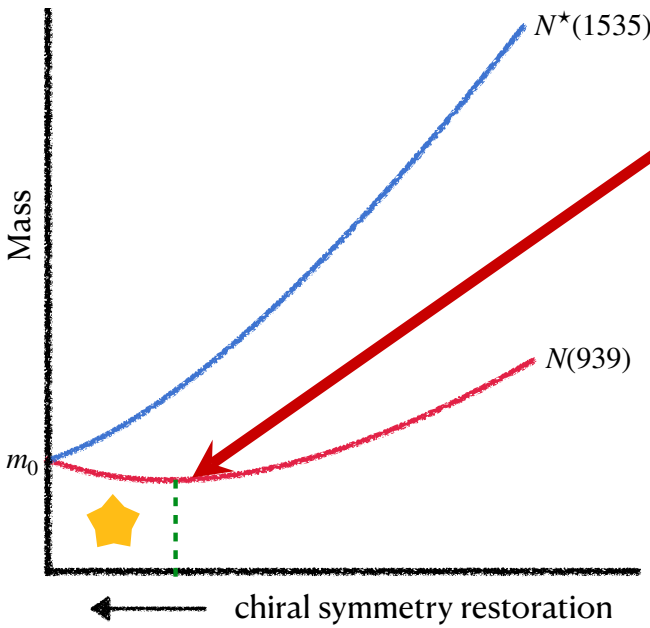


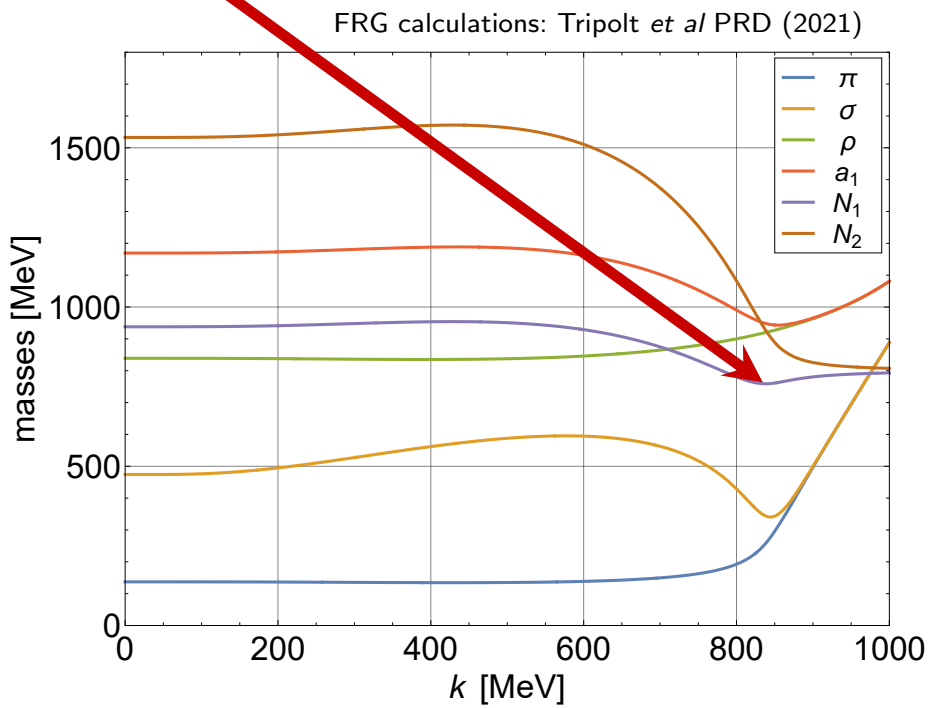


- Critical mode couples to $N(939)$ at liquid-gas phase transition
- Critical mode couples to $N(939)$ and $N^\star(1535)$ at chiral phase transition
- χ_2^+ becomes negative at small T

Chiral Critical Mode and Behavior of Nucleon Mass

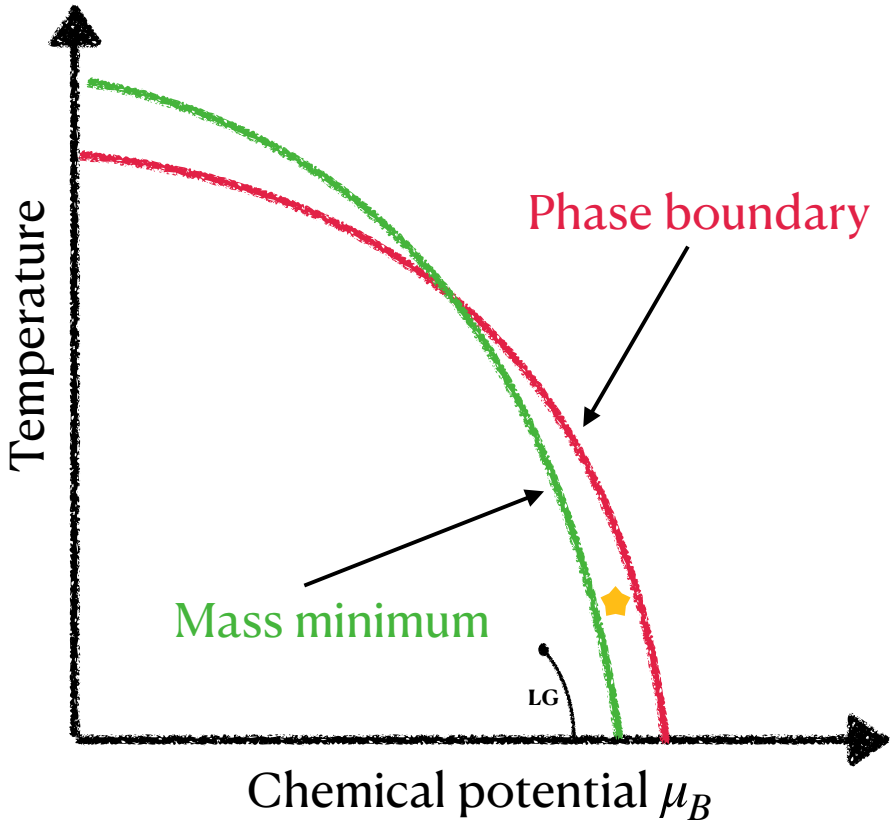
$$\chi_2^{\pm,\mathrm{crit}} \sim \frac{\partial n_B^{\pm}}{\partial m_{\pm}} \frac{\partial m_{\pm}}{\partial \sigma} \frac{\partial \sigma}{\partial \mu_B}$$

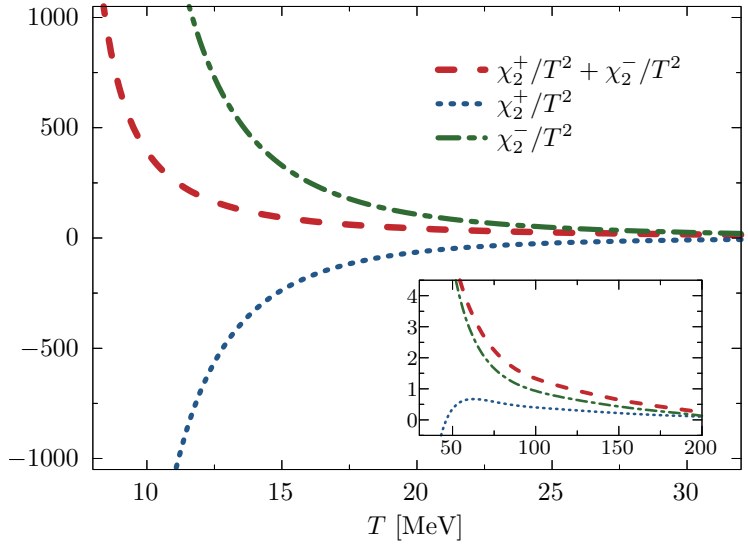


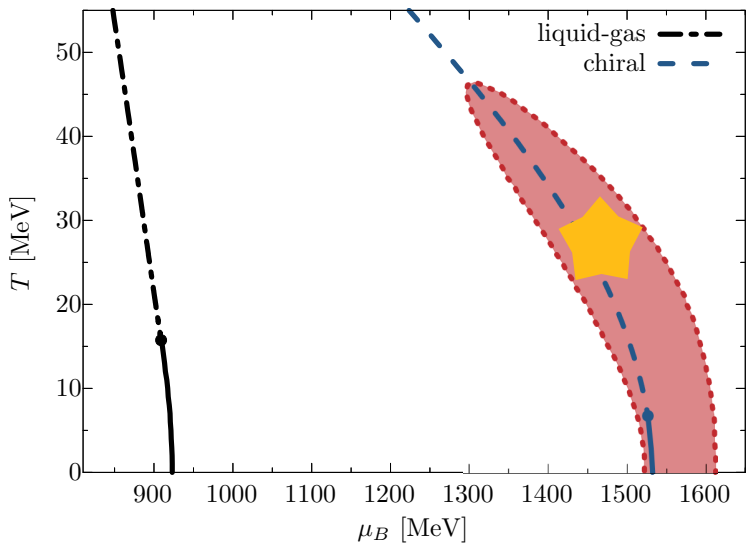


- $\chi_2^{\pm}$ diverge with the same critical exp. at CP
- Negativity of χ_2^{+} from the restoration of chiral symmetry

Approaching Critical Point at Phase Boundary







NET-PROTON AS PROXY FOR NET-BARYON

↓

COMMON LORE NOT NECESSARILY CORRECT

Summary

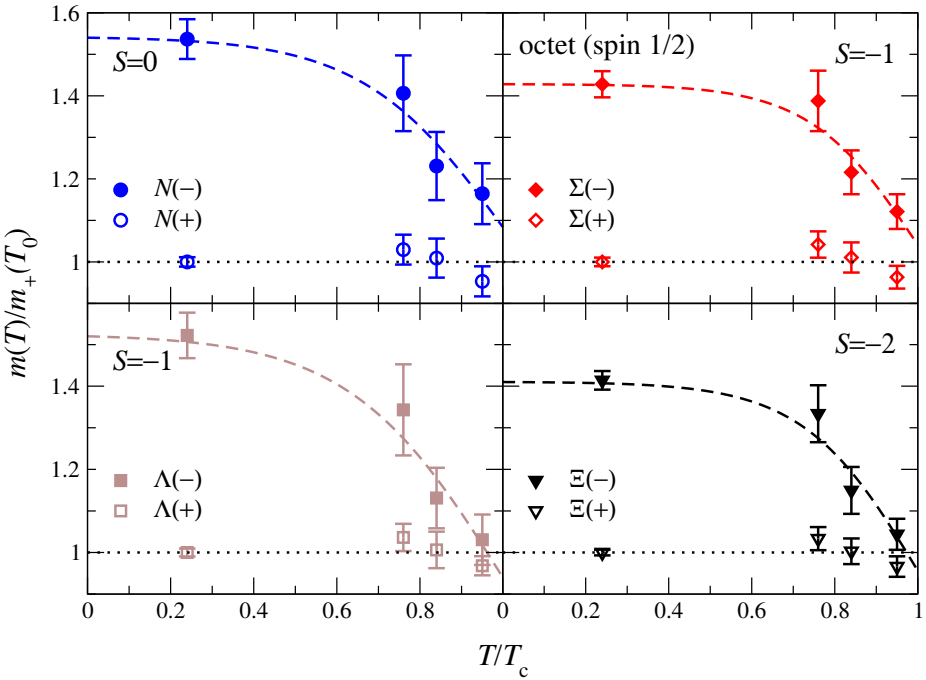
dominance of chiral criticality at phase boundary

net-proton $\leftrightarrow$ net-baryon not necessarily correct

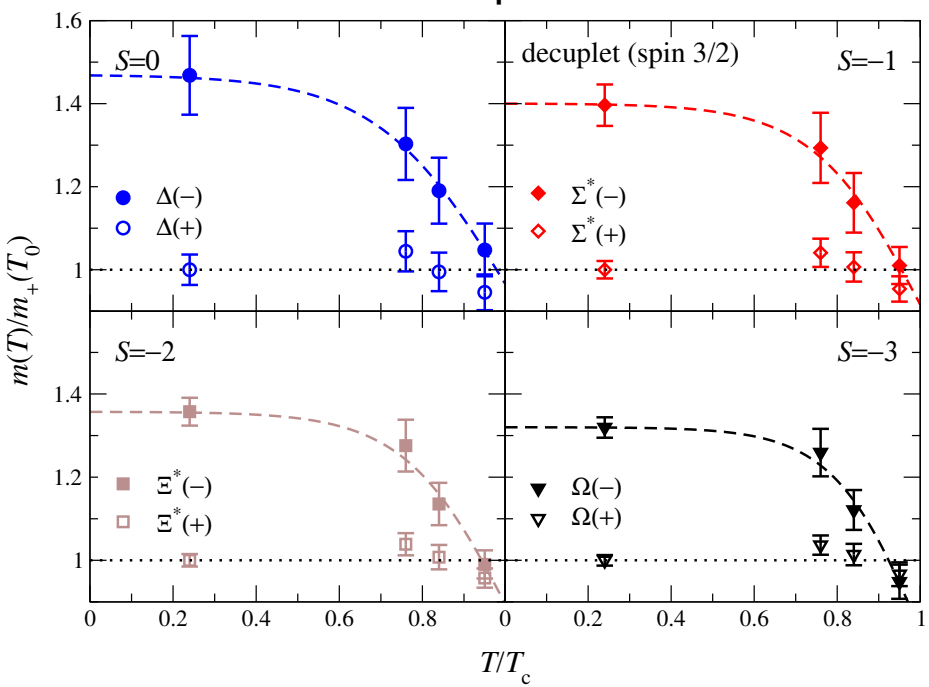
Thank You

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

Octet



Decouplet



Different decomposition

$$\chi_2^{\pm} = \frac{\frac{\partial n_B^{\pm}}{\partial \mu_B} + \chi_2^{\pm,\mathrm{crit}}}{1 + g_\omega \frac{\partial n_B^{\pm}}{\partial \mu_B}}$$