Van der Waals interactions in Hadron Resonance Gas: from Nuclear Matter to Lattice QCD

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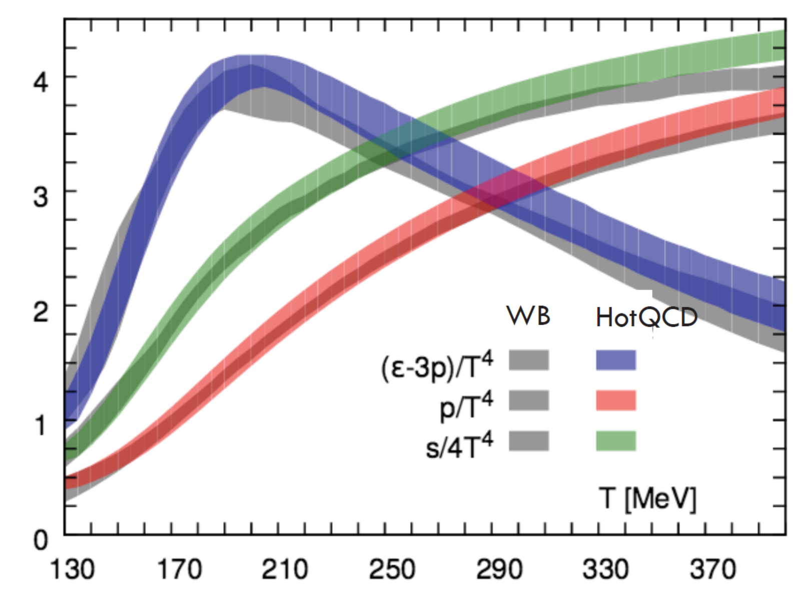
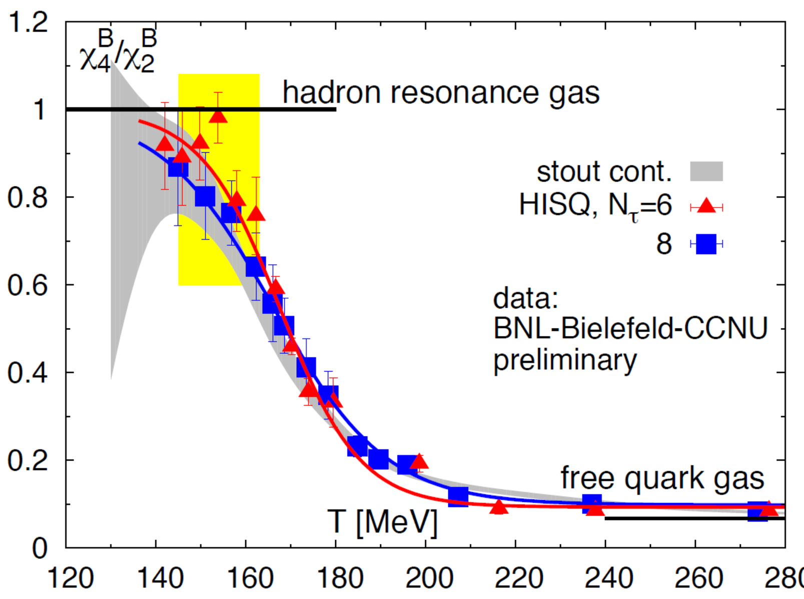
Introduction

Lattice QCD simulations provide equation of state of strongly interacting matter at $\mu = 0$[1,2]





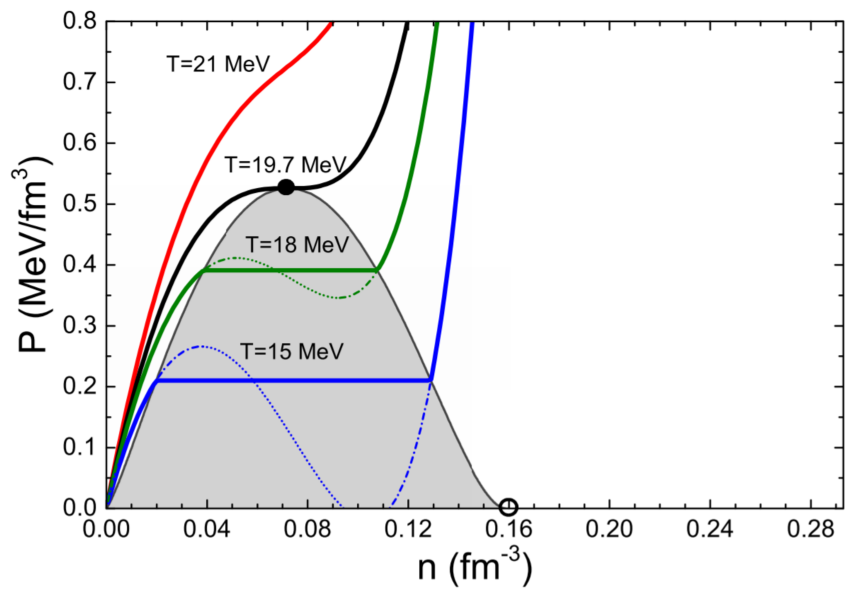
- Common model for confined phase is ideal HRG
- Good description of thermodynamic functions up to 180 MeV
- Rapid breakdown in crossover region for description of susceptibilities
- Often interpreted as clear signal of deconfinement…
- But what is the role of hadronic interactions beyond normal HRG?

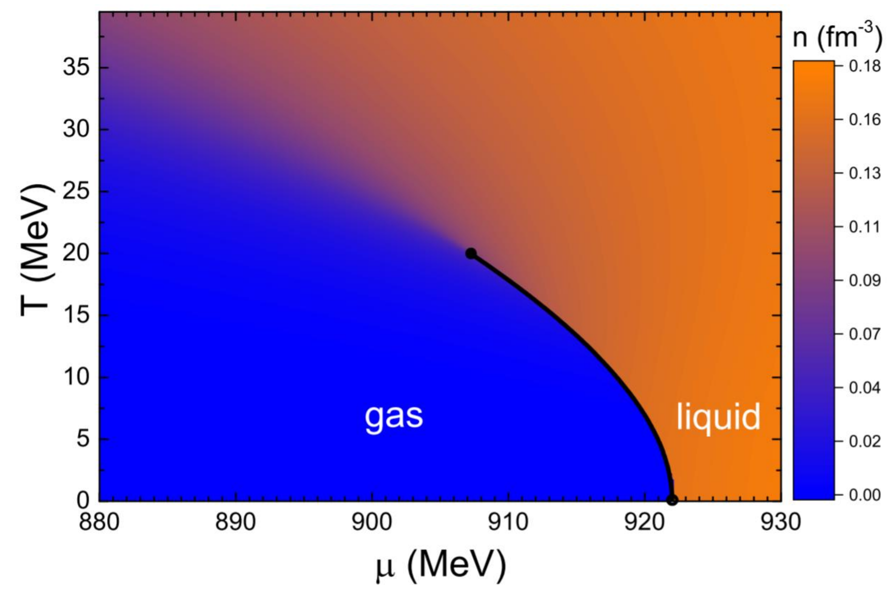
Nuclear matter as a van der Waals system

Nucleon-nucleon interaction is repulsive at small distances and attractive at intermediate ones

Suggestive similarity to van der Waals interactions

$$P(T,n) = P^{id}\left(T, \frac{n}{1-bn}\right) - an^2$$





- Basic properties of nuclear matter are described by fermionic VDW equation for nucleons
- Fit to nuclear ground state yields $a = 329$ MeV fm^3, $b = 3.42$ fm^3
- Fits within other VDW-like real gas models yield[4] $a = 330 - 430$ MeV fm^3, $b = 2.5 - 4.3$ fm^3

VDW-HRG model

Assumptions:

- Same VDW interactions between all pairs of baryons and between all pairs of antibaryons
- Baryon-antibaryon, meson-meson meson-(anti)baryon VDW interactions are neglected
- VDW parameters of baryon-baryon interaction taken from fit to nuclear ground state

Three independent subsystems: mesons + baryons + antibaryons

$$P(T,\mu) = P_M(T,\mu) + P_B(T,\mu) + P_{\bar{B}}(T,\mu)$$

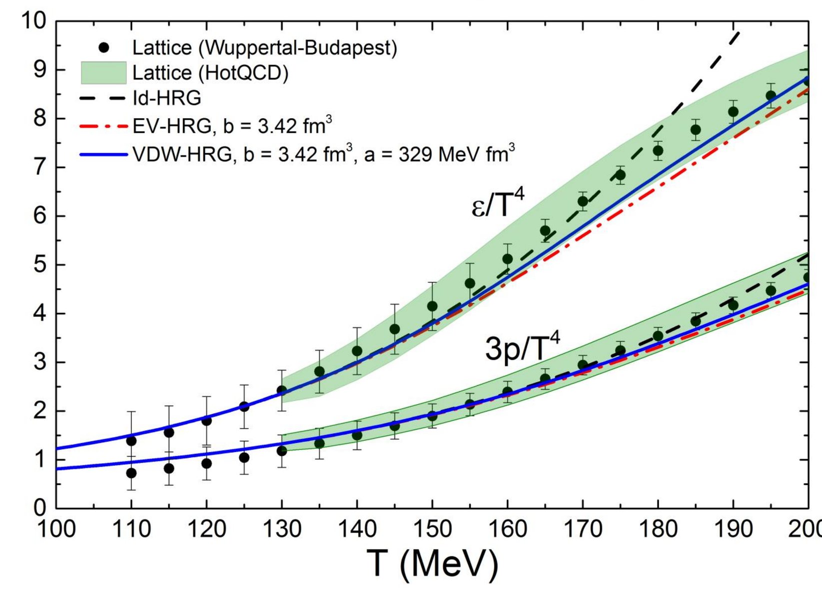
$$P_M(T,\mu) = \sum_{j\in M} P_j^{id}(T,\mu_j) \quad \text{and} \quad P_B(T,\mu) = \sum_{j\in B} P_j^{id}(T,\mu_j^*) - an_B^2$$

$$n_B(T,\mu) = (1 - bn_B)\sum_{j\in B} n_j^{id}(T,\mu_j^*), \qquad \mu_j^* = \mu_j - b\sum_{j\in B} P_j^{id}(T,\mu_j^*) + 2an_B$$

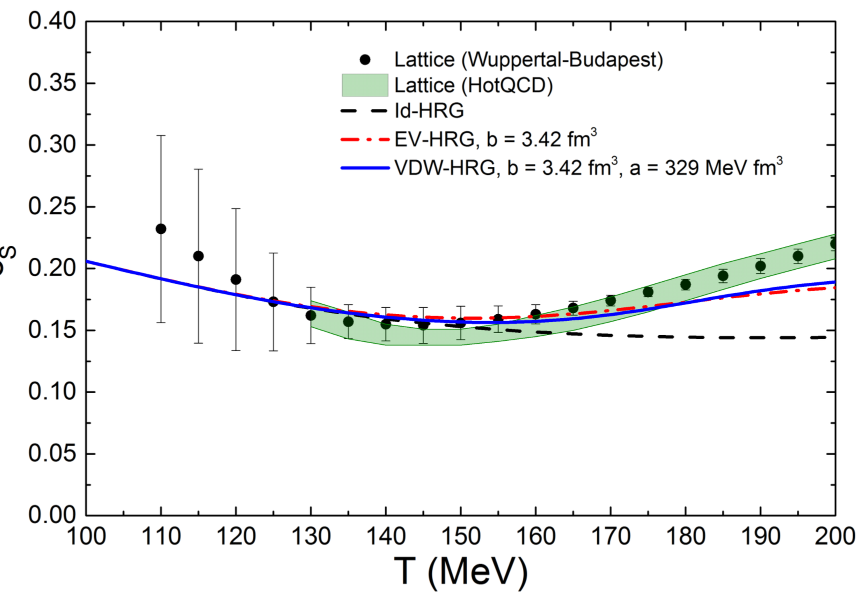
- Technical side: transcendental equations for P_B and n_B
- In this simplest setup VDW-HRG model is essentially "parameter-free"[3]

VDW-HRG vs Lattice QCD: Equation of State

Pressure and energy density



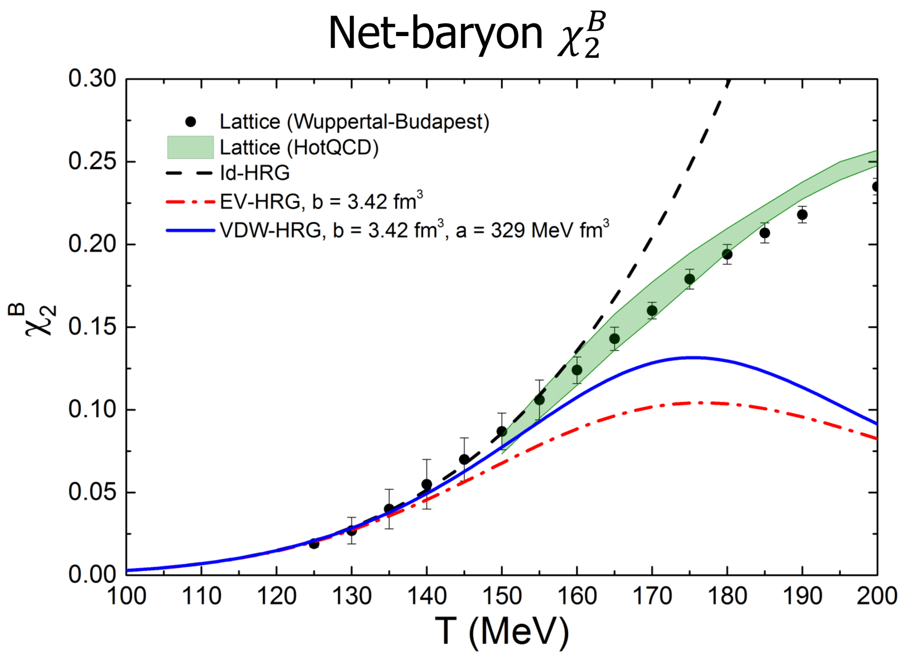
Speed of sound



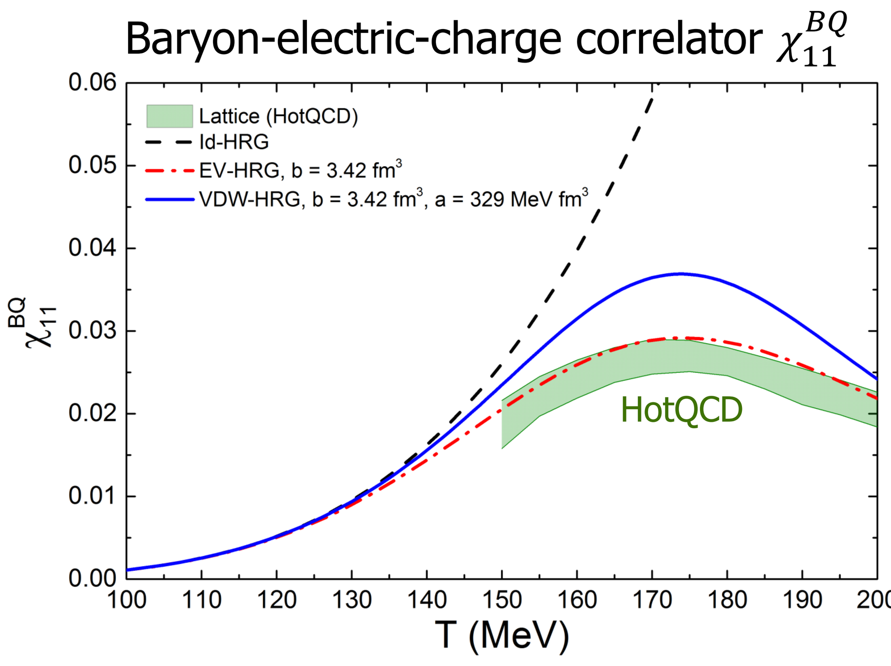
- VDW-HRG does not spoil existing agreement of ideal HRG with lattice QCD
- Not surprising: matter meson-dominated at $\mu = 0$
- Qualitatively different behavior of c_s^2, VDW-HRG consistent with lattice

VDW-HRG vs Lattice QCD: Fluctuations and correlations

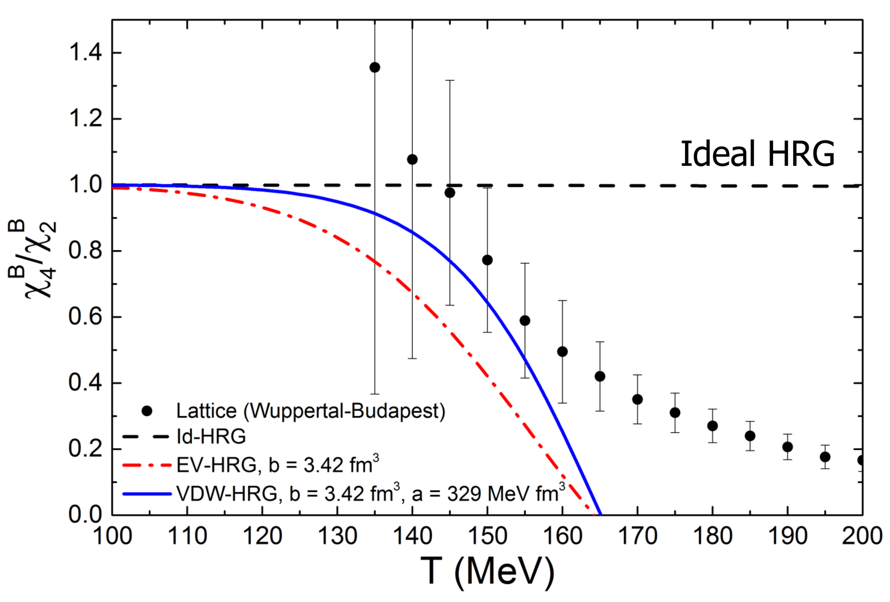
Net-baryon χ_2^B



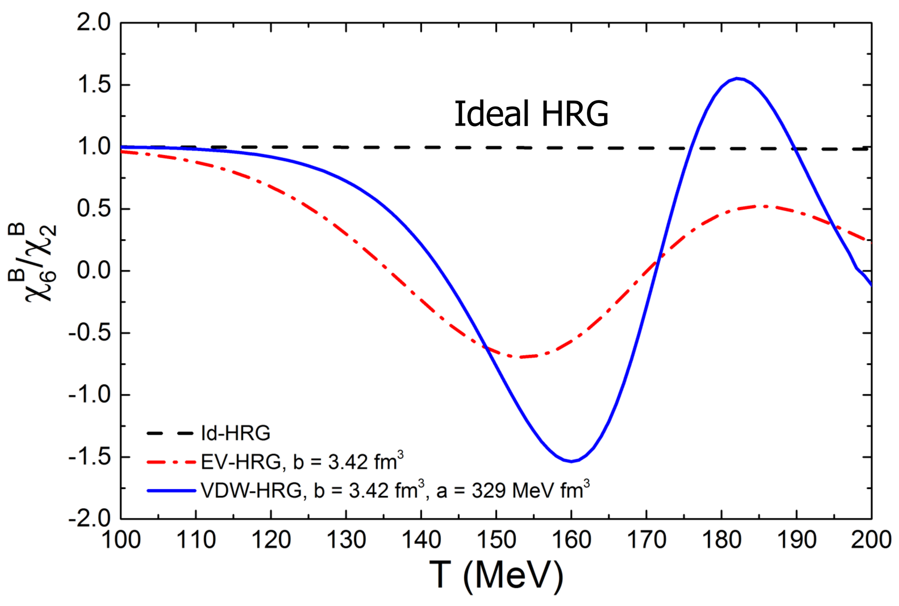
Baryon-electric-charge correlator χ_{11}^{BQ}



Net-baryon kurtosis χ_4^B/χ_2^B

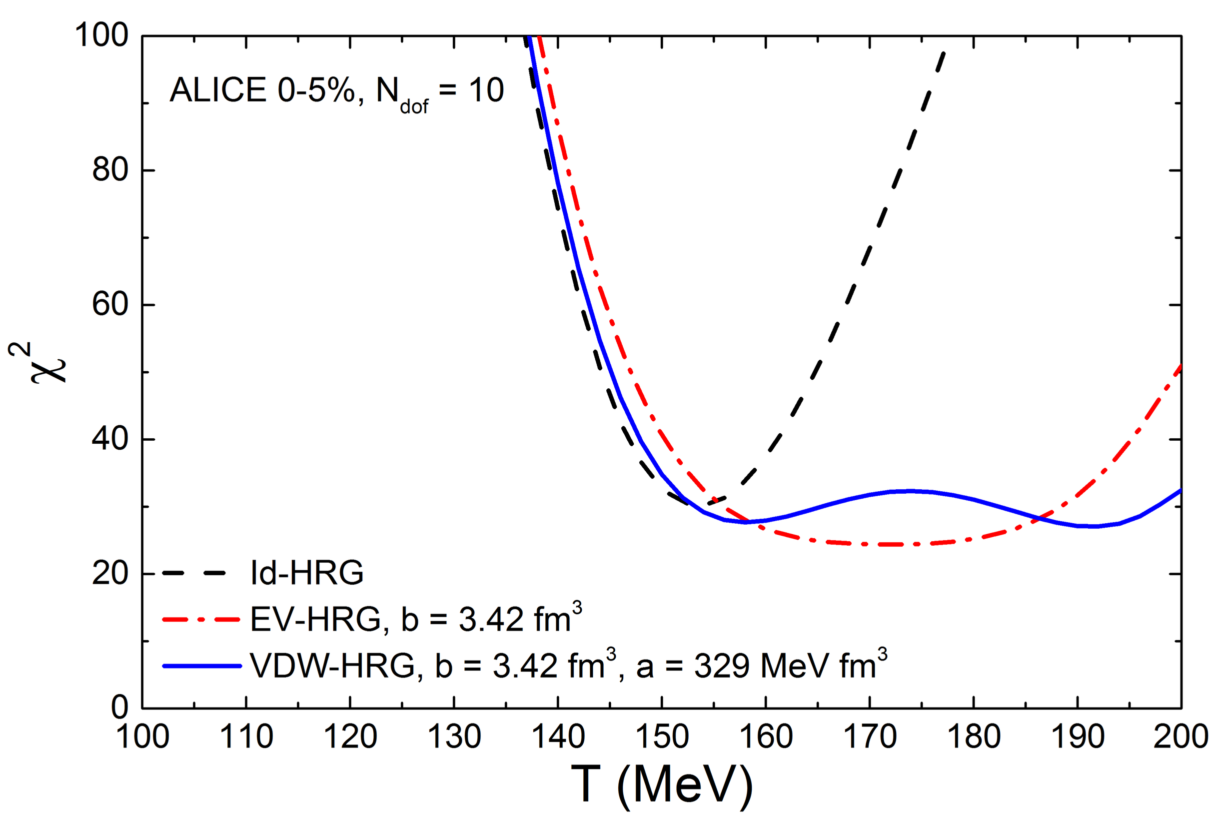


Net-baryon χ_6^B/χ_2^B



- Ideal and VDW HRG give qualitatively different behavior in the crossover region
- Agreement can be improved by taking smaller eigenvolume => smaller strange states?[5]
- Similarly strong effects also for net-strangeness and net-light quark number fluctuations
- Hadronic VDW interactions describe onset of deviations of ideal HRG from lattice data

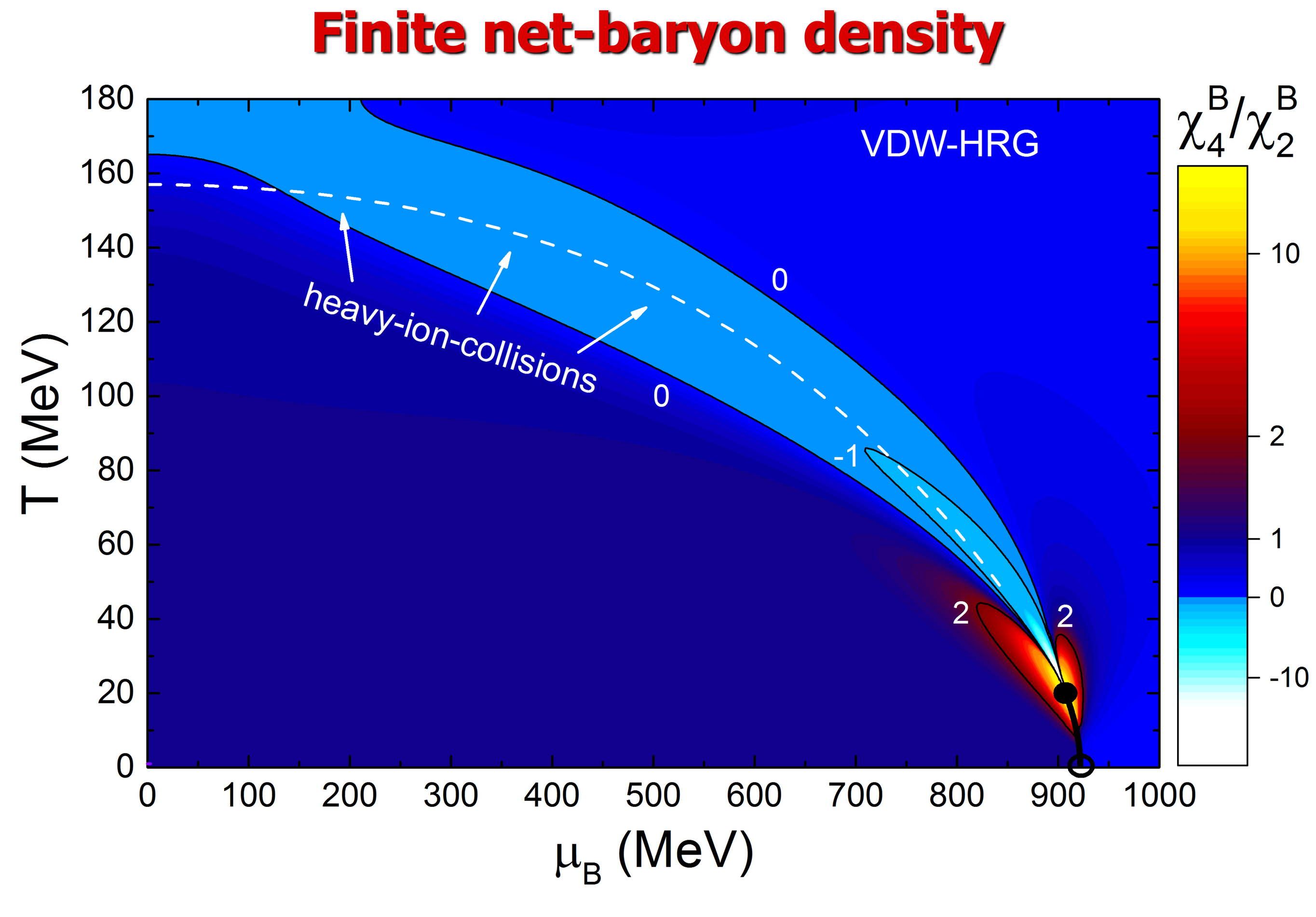
Thermal fits



- Pb+Pb at 2.76 TeV
- 0-5% centrality
- ALICE dN/dy data
- $\pi^\pm, K^\pm, p, \bar{p}, \Lambda, \Xi^\pm, \Omega, K_0^S, \phi$

- VDW interactions change relative hadron yields, give very different thermal fit picture!
- In VDW-HRG all temperatures between 150 and 200 MeV give fair description of data

Finite net-baryon density



- Rich structure of kurtosis of net-baryon number fluctuations in VDW-HRG
- Fluctuations seen at RHIC are remnants of the nuclear liquid-gas phase transition?[3]

Summary

- ✓ The VDW-HRG model captures basic features of both nuclear matter and lattice QCD data at zero chemical potential
- ✓ Van der Waals interactions lead to major qualitative changes in behavior of fluctuations of conserved charges
- ✓ Agreement with heavy-ion hadron yield data is improved at high temperatures in VDW-HRG model
- ✓ Nuclear liquid-gas criticality plays major role for net-baryon fluctuations in regions probed by heavy-ion collisions

References

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