

van der Waals Interactions and Hadron Resonance Gas: From Nuclear Matter to Lattice QCD

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- V.V, M. Gorenstein, H. Stoecker, [Phys. Rev. Lett. 118, 182301 \(2017\)](#)
- V.V, [arXiv:1701.06524](#), Phys. Rev. C, in print

Thanks to: P. Alba, S. Borsányi, Z. Fodor, M. Gorenstein,
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SQM 2017, Utrecht, Netherlands

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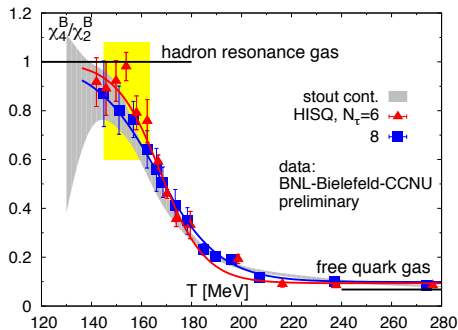
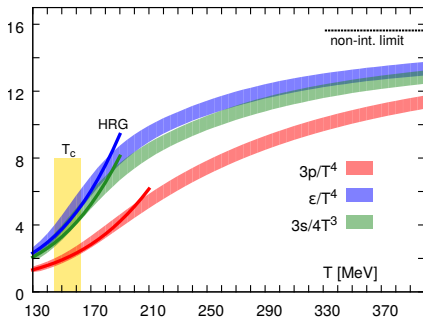
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- Motivation
- (Quantum) van der Waals equation in QCD
 - Nuclear matter
 - Baryonic sector in HRG
 - Fluctuations of conserved charges and Lattice QCD
- Extensions
 - Beyond van der Waals
 - Beth-Uhlenbeck approach and quantum excluded volume
 - Imaginary chemical potential
- Summary

QCD equation of state at $\mu = 0$

Lattice simulations provide equation of state at $\mu_B = 0^1$



Common model for confined phase is **ideal HRG**: non-interacting gas of known hadrons and resonances

- Good description of thermodynamic functions up to 180 MeV
- Rapid **breakdown** in crossover region for description of **susceptibilities**²
- Often interpreted as clear signal of deconfinement...
- But what is the role of **hadronic interactions** beyond those in ideal HRG?

¹Bazavov et al., PRD 90, 094503 (2014); Borsanyi et al., PLB 730, 99 (2014)

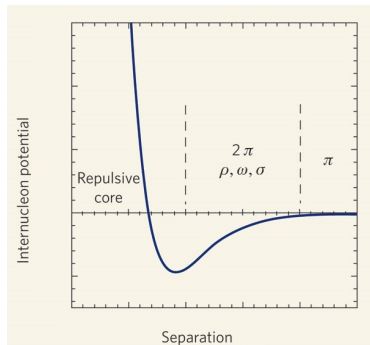
²Ding, Karsch, Mukherjee, IJMPA 24, 1530007 (2015)

Nucleon-nucleon interaction

Many hadronic interactions described by resonance formation... however

Nucleon-nucleon potential:

- Repulsive core at small distances
- Attraction at intermediate distances
- No resonance structure
- Suggestive similarity to VDW interactions
- Could nuclear matter be described by VDW equation?



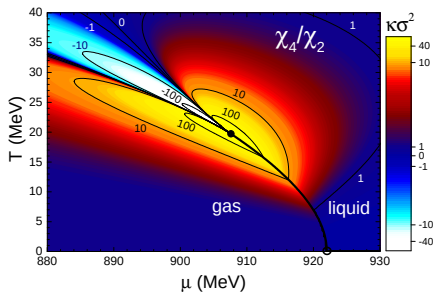
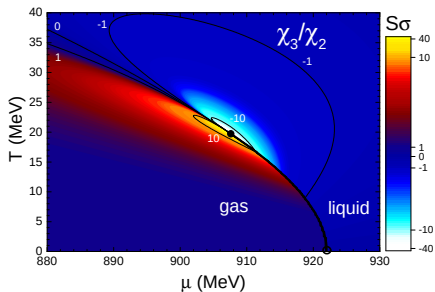
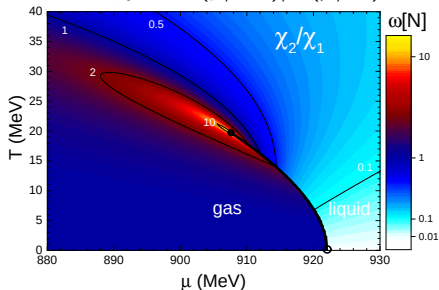
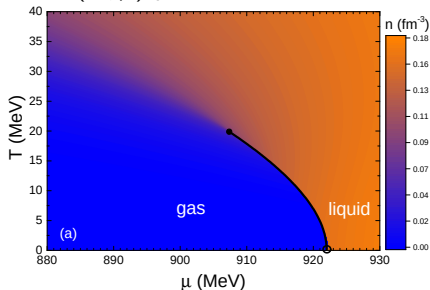
Nuclear matter with **quantum van der Waals equation**

$$p(T, n) = p_q^{\text{id}}\left(T, \frac{n}{1 - bn}\right) - a n^2$$

$$E/A = -16 \text{ MeV}, \quad n_0 = 0.16 \text{ fm}^{-3} \quad \Rightarrow \quad a_{NN} = 329 \text{ MeV fm}^3, \quad b_{NN} = 3.42 \text{ fm}^3$$

VDW gas of nucleons: (T, μ) plane

(T, μ) plane: structure of critical fluctuations $\chi_i = \partial^i(p/T^4)/\partial(\mu/T)^i$



van der Waals interactions in hadron resonance gas

Let us now include nuclear matter physics into HRG...

VDW-HRG model¹

- Identical VDW interactions between all baryons
- **Baryon-antibaryon, meson-meson, meson-baryon** VDW terms **neglected**
- Baryon VDW parameters extracted from ground state of nuclear matter ($a = 329 \text{ MeV fm}^3$, $b = 3.42 \text{ fm}^3$)

Three independent subsystems: **mesons** + **baryons** + **antibaryons**

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

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

In this simplest setup **model** is essentially “**parameter-free**”

Quite different from “**standard scenario**” for hadronic interactions in HRG: no attraction and **constant radius** for all mesons, baryons, light nuclei etc.²

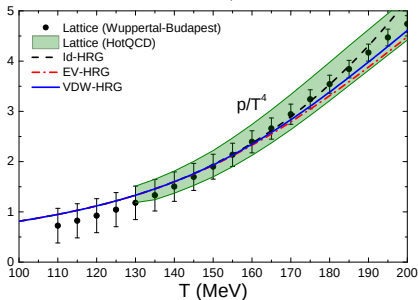
¹V.V., M. Gorenstein, H. Stoecker, Phys. Rev. Lett. 118, 182301 (2017)

²Andronic et al., PLB '12; Redlich, Zalewski, PRC '16; Cleymans, Randrup, EPJ '16

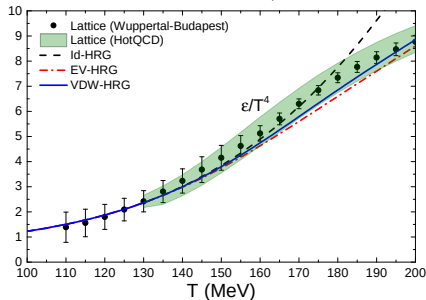
VDW-HRG at $\mu_B = 0$: thermodynamic functions

Comparison of VDW-HRG with lattice QCD at $\mu_B = 0$

Pressure p/T^4

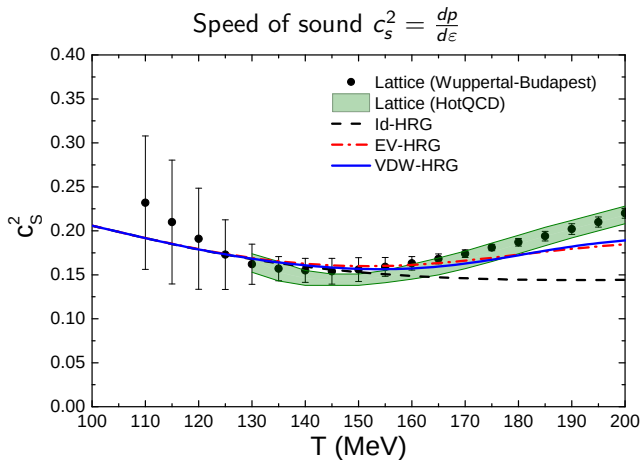


Energy density ε/T^4



- VDW-HRG **does not spoil** existing agreement of Id-HRG with LQCD despite significant excluded-volume interactions between baryons
- Not surprising: matter **meson-dominated** at $\mu_B = 0$

VDW-HRG at $\mu_B = 0$: speed of sound



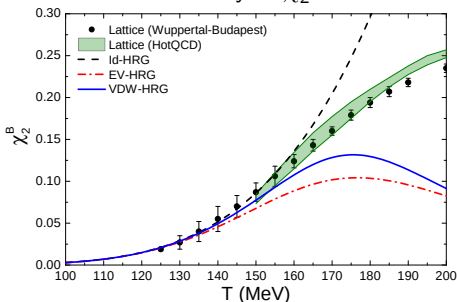
- Monotonic decrease in Id-HRG, at odds with lattice
- **Minimum** for EV-HRG/VDW-HRG at 150-160 MeV
- **No acausal behavior**, often an issue in models with eigenvolumes

V.V., M. Gorenstein, H. Stoecker, Phys. Rev. Lett. 118, 182301 (2017)

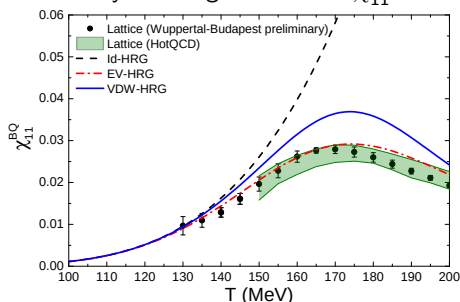
VDW-HRG at $\mu_B = 0$: baryon number fluctuations

$$\text{Susceptibilities: } \chi_{lmn}^{BSQ} = \frac{\partial^{l+m+n} p / T^4}{\partial(\mu_B/T)^l \partial(\mu_S/T)^m \partial(\mu_Q/T)^n}$$

Net-baryon χ_2^B

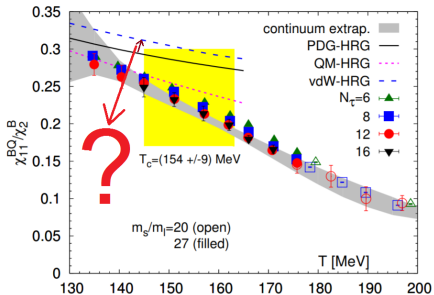


Baryon-charge correlator χ_{11}^{BQ}

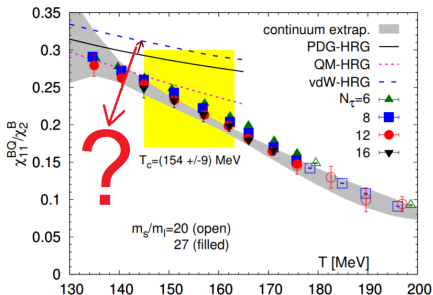


- Very **different qualitative** behavior between Id-HRG and VDW-HRG
- For χ_2^B lattice data is **between** Id-HRG and VDW-HRG at high T
- For χ_{11}^{BQ} lattice data is below all models, closer to EV-HRG

F. Karsch, QM2017, 1706.01620



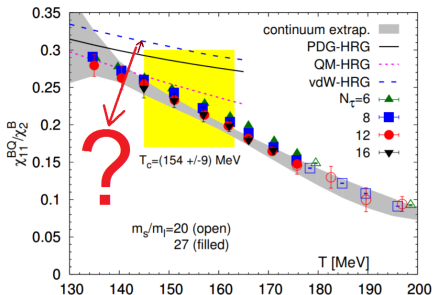
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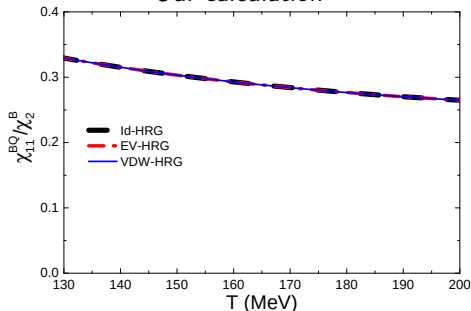
$$\left(\frac{\chi_{11}^{BQ}}{\chi_2^B} \right)_{\text{vdW}} = \frac{\sum_{i \in B} Q_i n_i^{\text{id}} f(n_B)}{\sum_{i \in B} n_i^{\text{id}} f(n_B)} = \frac{\sum_{i \in B} Q_i n_i^{\text{id}}}{\sum_{i \in B} n_i^{\text{id}}} = \left(\frac{\chi_{11}^{BQ}}{\chi_2^B} \right)_{\text{ideal}}$$

Ratio χ_{11}^{BQ}/χ_2^B

F. Karsch, QM2017, 1706.01620



Our calculation



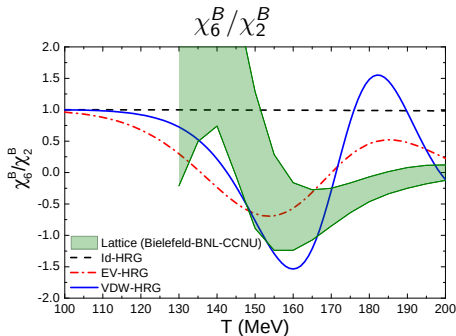
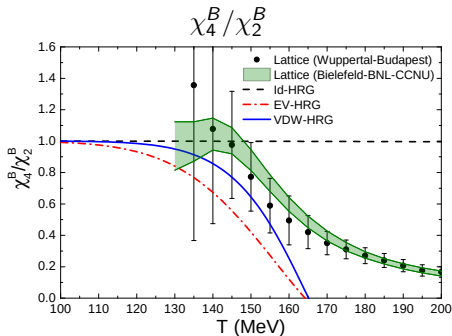
$$\left(\frac{\chi_{11}^{BQ}}{\chi_2^B} \right)_{\text{vdW}} = \frac{\sum_{i \in B} Q_i n_i^{\text{id}} f(n_B)}{\sum_{i \in B} n_i^{\text{id}} f(n_B)} = \frac{\sum_{i \in B} Q_i n_i^{\text{id}}}{\sum_{i \in B} n_i^{\text{id}}} = \left(\frac{\chi_{11}^{BQ}}{\chi_2^B} \right)_{\text{ideal}}$$

- The χ_{11}^{BQ}/χ_2^B ratio is unaffected within VDW-HRG model, proof is **analytic**
- **Quark model** states and/or **flavor dependent** interactions improve description¹

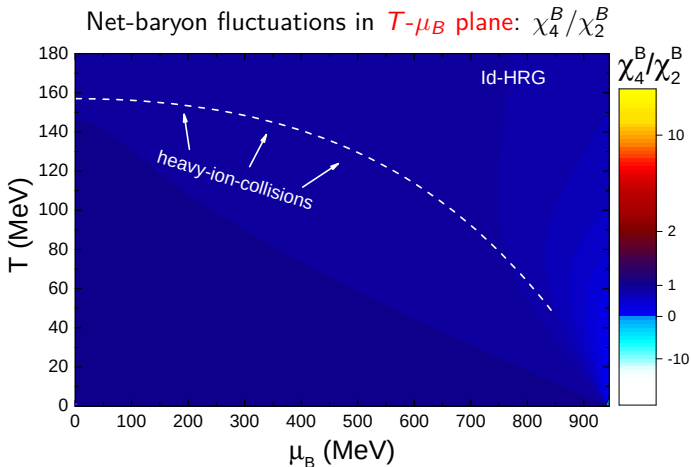
¹See also **P. Alba's talk** on Friday

VDW-HRG at $\mu_B = 0$: baryon number fluctuations

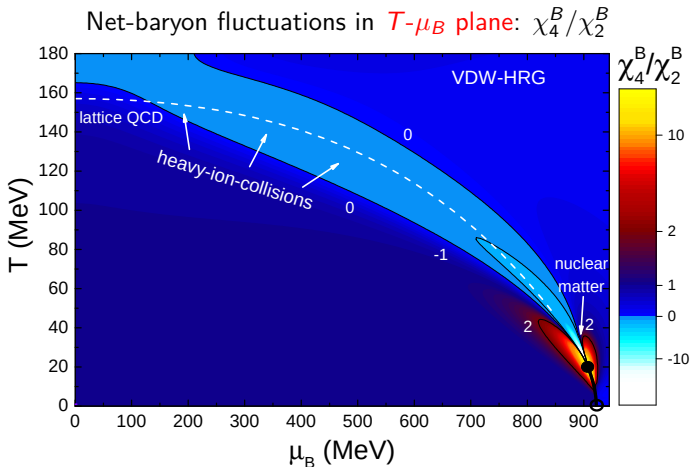
Higher-order fluctuations are expected to be even more sensitive



- χ_4^B deviates from χ_2^B at high enough T , they stay equal in Id-HRG
- Cannot be related only to onset of deconfinement
- VDW-HRG predicts strong non-monotonic behavior for χ_6^B / χ_2^B



- Almost **no effect** in **Id-HRG**, only Fermi statistics...



- Almost **no effect** in **Id-HRG**, only Fermi statistics...
- Rather **rich structure** for **VDW-HRG**, huge effect of VDW interactions!
- Fluctuations seen at RHIC are remnants of **nuclear liquid-gas PT?**

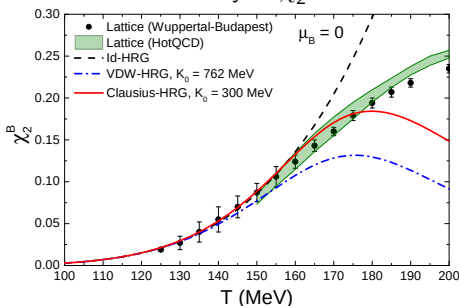
Beyond van der Waals

From **van der Waals** equation to **Clausius** equation:

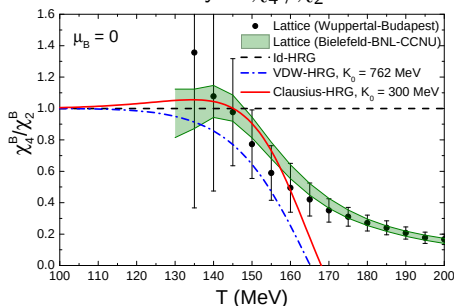
$$p = \frac{nT}{1 - bn} - a n^2 \quad \Rightarrow \quad p = \frac{nT}{1 - bn} - \frac{a n^2}{1 + cn}$$

Nuclear incompressibility K_0 : from **762 MeV** in **VDW** to **300 MeV** in **Clausius**
Clausius-HRG: baryon-baryon interactions in HRG with Clausius equation

net baryon χ_2^B



net baryon χ_4^B / χ_2^B

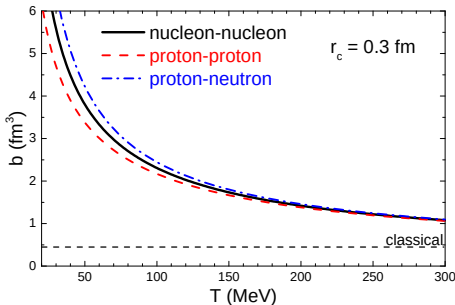


- Clausius-HRG yields improved K_0 and improved description of LQCD
- Behavior of **LQCD observables** correlates with **nuclear matter properties**

Hard-core repulsion: classical vs Beth-Uhlenbeck

QM approach to NN hard-core repulsion: **Beth-Uhlenbeck (BU)** formula

$$\Delta p^{\text{int}} \propto B_2(T) = \frac{T}{2\pi^3} \int_{2m_N}^{\infty} d\varepsilon \varepsilon^2 K_2(\varepsilon/T) \sum_{J,T} (2J+1)(2T+1) \frac{\partial \delta_{J,T}(\varepsilon)}{\partial \varepsilon}$$



$$\delta_{J,T}(\varepsilon) = \arctan \left\{ \frac{j_L[2r_c q(\varepsilon)]}{y_L[2r_c q(\varepsilon)]} \right\}$$

Beth-Uhlenbeck eigenvolume:

$$b = b(T) = -B_2(T)/[n^{\text{id}}(T)]^2$$

Classical eigenvolume:

$$p = p^{\text{id}}(T, \mu - bp), \quad b = \frac{16\pi r_c^3}{3}$$

NN-scattering data¹: $r_c \simeq 0.25\text{-}0.3$ fm

- EV of nucleon-nucleon interaction is **strongly T -dependent** due to QM effects
- **Classical** approach² **underestimates EV** by factor 3-4 at $T \sim 100 - 200$ MeV³

¹R. B. Wiringa et al., Phys. Rev. C **51**, 38 (1995)

²A. Andronic et al., Phys. Lett. B **718**, 80 (2012); K. Redlich, K. Zalewski, PRC '16

³similar conclusions for spinless particles in Kostyuk et al., PRC '01; S. Typel, EPJA '16

Hard-core repulsion: classical vs Beth-Uhlenbeck

Now let us use this T -dependent eigenvolume $b(T)$ to model BB repulsion in HRG

$$\text{BU-HRG: } P_B(T, \mu) = \sum_{i \in B} p_i^{\text{id}}(T, \mu_B) - T b(T) \sum_{i,j} \phi_i(T) \phi_j(T) \lambda_B^2$$

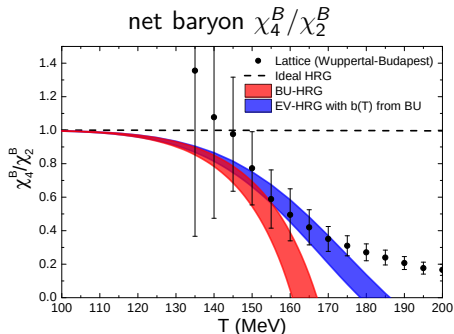
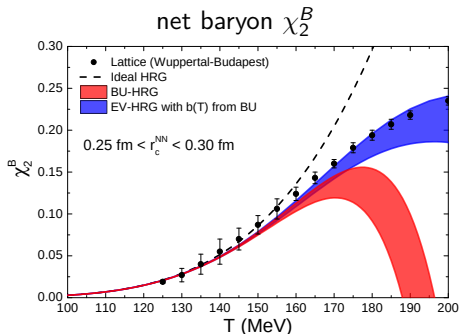
$$\text{EV-HRG: } P_B(T, \mu) = \sum_{i \in B} p_i^{\text{id}}[T, \mu_B - b(T) P_B]$$

Hard-core repulsion: classical vs Beth-Uhlenbeck

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EV-HRG:
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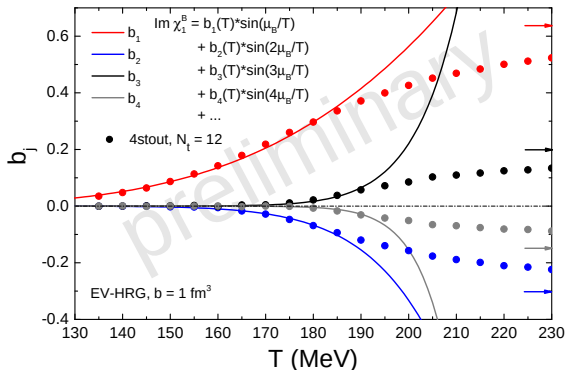
- Pure BU approach **breaks down** at high T , **higher orders** matter!
- EV-HRG with BU-motivated $b \sim 1 - 2 \text{ fm}^3$ **describes LQCD** fairly well

Repulsive baryonic interactions and imaginary μ_B

Lattice QCD is problematic at real μ but tractable at **imaginary μ**

E.g., net-baryon density is **imaginary** and has **trigonometric series** form

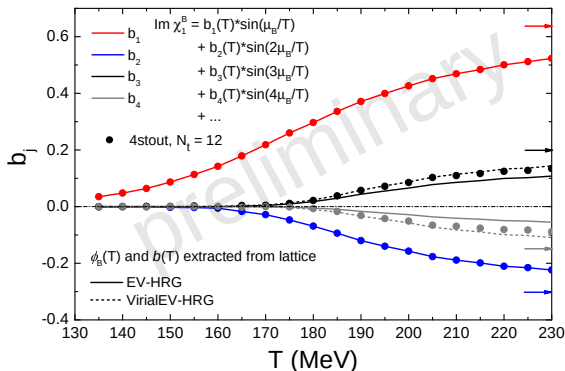
$$\mu_B \rightarrow i\tilde{\mu}_B \Rightarrow \frac{n_B(T, i\tilde{\mu}_B)}{T^3} = i \sum_{j=1}^{\infty} b_j(T) \sin(j \tilde{\mu}_B/T)$$



- Non-zero $b_j(T)$ for $j \geq 2$ signal deviations from ideal HRG
- Addition of EV interactions between baryons **reproduces lattice trend**

$$\mu_B \rightarrow i\tilde{\mu}_B \Rightarrow \frac{n_B(T, i\tilde{\mu}_B)}{T^3} = i \sum_{j=1}^{\infty} b_j(T) \sin(j \tilde{\mu}_B/T)$$

- Fix baryon spectrum and BB EV parameter from b_1 and b_2
- Predict b_3 and b_4



- EV approach appears to have predictive power, even at high T
- Variations on EV mechanism should be considered

Summary

- van der Waals interactions between baryons in HRG change **qualitative** behavior of **fluctuations of conserved charges** in the crossover region
- Interpretation within standard **ideal HRG** should be done with **extreme care**, not clear how useful are ideal HRG vs LQCD comparisons in crossover region
- **Nuclear liquid-gas** transition manifests itself into non-trivial **net-baryon fluctuations** in regions of phase diagram probed by heavy-ion collisions
- Classical EV approach underestimates 2nd virial coefficient of hard-core repulsion by **factor 3-4** at typical for HIC temperature scales
- LQCD observables at **imaginary μ** are promising in studying hadronic interactions

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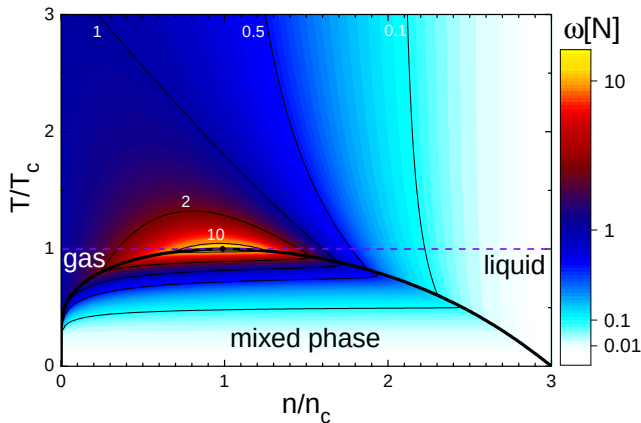
Thanks for your attention!

Backup slides

Scaled variance for classical VDW equation

Particle number fluctuations in classical VDW gas within GCE

$$\omega[N] = \frac{\langle N^2 \rangle - \langle N \rangle^2}{\langle N \rangle} = \frac{\chi_2}{\chi_1} = \left[\frac{1}{(1 - bn)^2} - \frac{2an}{T} \right]^{-1}$$

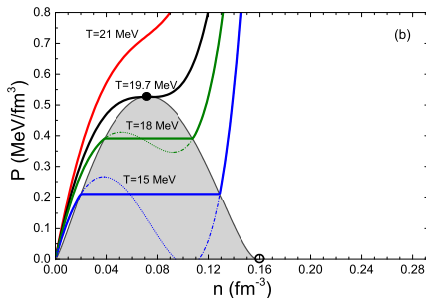
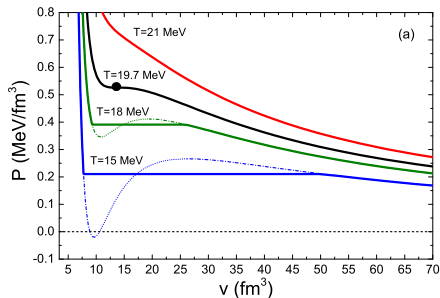


- Repulsive interactions suppress N-fluctuations
- Attractive interactions enhance N-fluctuations

VDW gas of nucleons: pressure isotherms

a and b fixed to reproduce **saturation density** and **binding energy**:

$$n_0 = 0.16 \text{ fm}^{-3}, E/A = -16 \text{ MeV} \Rightarrow a \cong 329 \text{ MeV fm}^3 \text{ and } b \cong 3.42 \text{ fm}^3$$



Behavior qualitatively **same** as for Boltzmann case

Mixed phase results from **Maxwell construction**

Critical point at $T_c \cong 19.7 \text{ MeV}$ and $n_c \cong 0.07 \text{ fm}^{-3}$

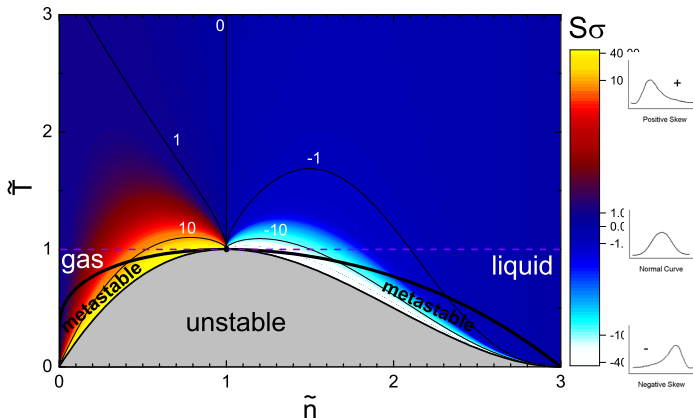
Experimental estimate¹: $T_c = 17.9 \pm 0.4 \text{ MeV}$, $n_c = 0.06 \pm 0.01 \text{ fm}^{-3}$

¹J.B. Elliot, P.T. Lake, L.G. Moretto, L. Phair, Phys. Rev. C 87, 054622 (2013)

Skewness

Higher-order (non-gaussian) fluctuations are even more sensitive

Skewness: $S\sigma = \frac{\langle(\Delta N)^3\rangle}{\sigma^2} = \omega[N] + \frac{T}{\omega[N]} \left(\frac{\partial \omega[N]}{\partial \mu} \right)_T$ asymmetry

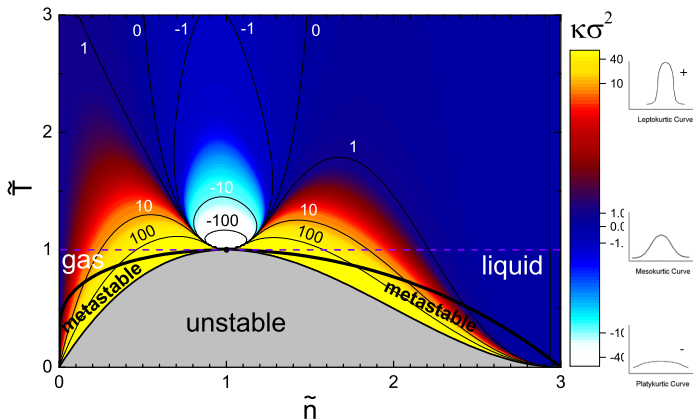


Skewness is

- Positive (right-tailed) in gaseous phase
- Negative (left-tailed) in liquid phase

Kurtosis: $\kappa\sigma^2 = \frac{\langle(\Delta N)^4\rangle - 3\langle(\Delta N)^2\rangle^2}{\sigma^2}$

peakedness



Kurtosis is **negative** (flat) above critical point (crossover), **positive** (peaked) elsewhere and very **sensitive** to the **proximity** of the critical point

V. Vovchenko et al., J. Phys. A 015003, 49 (2016)

Quantum statistical van der Waals fluid

Free energy of classical VDW fluid:

$$F(T, V, N) = F^{\text{id}}(T, V - bN, N) - a \frac{N^2}{V}$$

Ansatz: $F^{\text{id}}(T, V - bN, N)$ is free energy of ideal *quantum* gas

$$\text{Pressure:} \quad p = - \left(\frac{\partial F}{\partial V} \right)_{T, N} = p^{\text{id}}(T, \mu^*) - a n^2$$

$$\text{Particle density:} \quad n = \left(\frac{\partial p}{\partial \mu} \right)_T = \frac{n^{\text{id}}(T, \mu^*)}{1 + b n^{\text{id}}(T, \mu^*)}$$

$$\text{Shifted chemical potential:} \quad \mu^* = \mu - b p - a b n^2 + 2 a n$$

Model properties:

- Reduces to classical VDW equation when quantum statistics are negligible
- Reduces to ideal quantum gas for $a = 0$ and $b = 0$
- Entropy density non-negative and $s \rightarrow 0$ with $T \rightarrow 0$

V.V., Anchishkin, Gorenstein, JPA '15 and PRC '15; Redlich, Zalewski, APPB '16.
 $a=0 \Rightarrow$ **excluded-volume model**, D. Rischke et al., ZPC '91

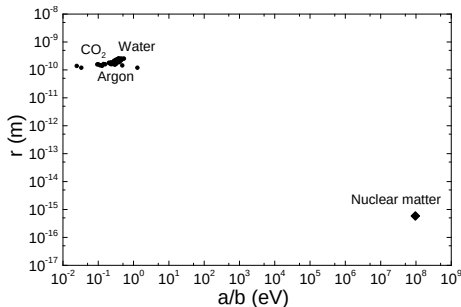
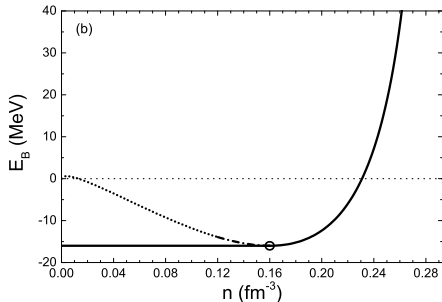
VDW gas of nucleons: zero temperature

How to fix a and b ? For classical fluid usually tied to CP location.

Different approach: Reproduce **saturation density** and **binding energy**

From $E_B = E/A \cong -16$ MeV and $n = n_0 \cong 0.16 \text{ fm}^{-3}$ at $T = 0$ and $p = 0$

$$a \cong 329 \text{ MeV fm}^3 \text{ and } b \cong 3.42 \text{ fm}^3$$



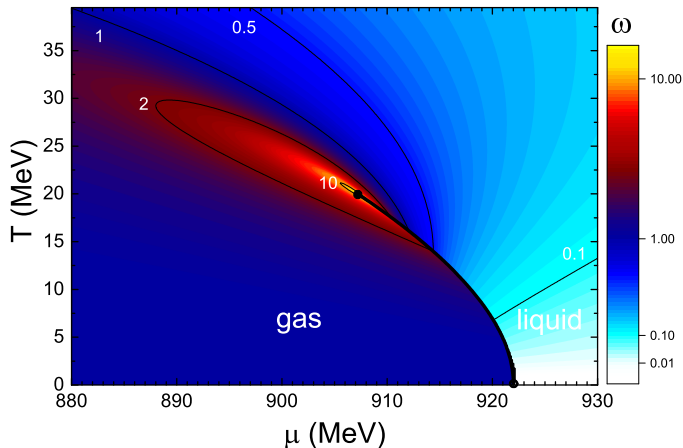
Mixed phase at $T = 0$ is specific:
A mix of vacuum ($n = 0$) and liquid at
 $n = n_0$

VDW eq. now at very different scale!

VDW gas of nucleons: scaled variance

Scaled variance in quantum VDW:

$$\omega[N] = \omega_{\text{id}}(T, \mu^*) \left[\frac{1}{(1 - bn)^2} - \frac{2an}{T} \omega_{\text{id}}(T, \mu^*) \right]^{-1}$$



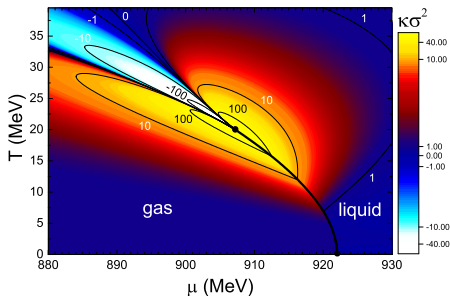
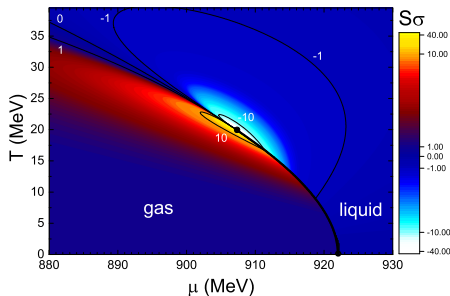
VDW gas of nucleons: skewness and kurtosis

Skewness

$$S\sigma = \omega[N] + \frac{T}{\omega[N]} \left(\frac{\partial \omega[N]}{\partial \mu} \right)_T$$

Kurtosis

$$\kappa\sigma^2 = (S\sigma)^2 + T \left(\frac{\partial [S\sigma]}{\partial \mu} \right)_T$$

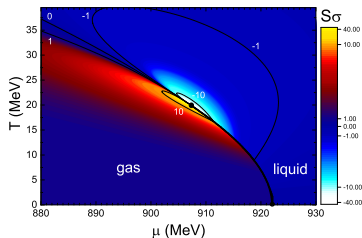


For skewness and kurtosis singularity is rather specific: sign depends on the path of approach

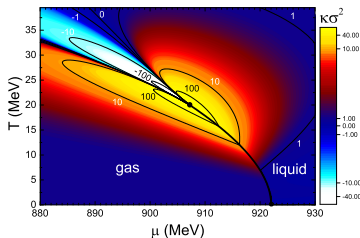
V. Vovchenko et al., Phys. Rev. C 92, 054901 (2015)

VDW gas of nucleons: skewness and kurtosis

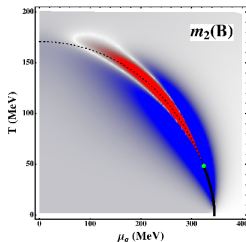
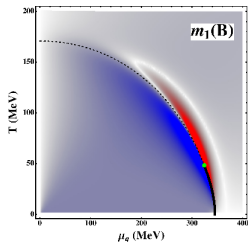
VDW Skewness



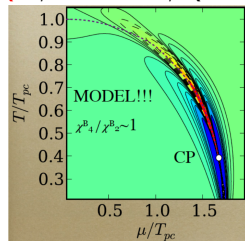
VDW Kurtosis



NJL, J.W. Chen et al., PRD 93, 034037 (2016)



PQM, V. Skokov, QM2012



Fluctuation patterns in VDW very similar to effective QCD models

Strongly intensive measures near CP

Strongly intensive (SI) measures: Gorenstein, Gazdzicki, PRC 84, 014904 (2011)

- Independent of **volume fluctuations**, mitigate impact parameter fluctuations
- Can be constructed from moments of **two** extensive quantities

$$\Delta[A, B] = C_{\Delta}^{-1} [\langle A \rangle \omega[B] - \langle B \rangle \omega[A]]$$

$$\Sigma[A, B] = C_{\Sigma}^{-1} [\langle A \rangle \omega[B] + \langle B \rangle \omega[A] - 2(\langle AB \rangle - \langle A \rangle \langle B \rangle)]$$

- For most models without PT and CP equal/close to unity
- Supposedly show **critical behavior**, but **no model calculation**
- Used in search for CP, e.g. **NA61/SHINE** program¹

SI measures of excitation energy and particle number fluctuations in cl. VDW

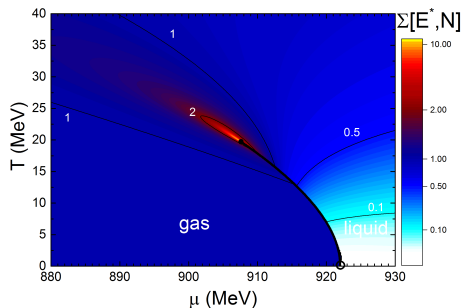
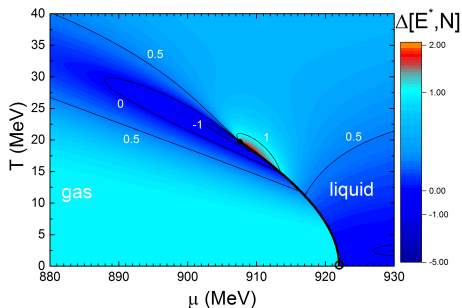
$$\Delta[E^*, N] = 1 - \frac{an(2\bar{\epsilon}_{\text{id}} - 3an)}{\bar{\epsilon}_{\text{id}}^2 - \bar{\epsilon}_{\text{id}}} \omega[N], \quad \Sigma[E^*, N] = 1 + \frac{a^2 n^2}{\bar{\epsilon}_{\text{id}}^2 - \bar{\epsilon}_{\text{id}}} \omega[N].$$

- **Critical behavior is present** due to criticality of $\omega[N]$ term²
- If $a=0$ then **no signal at all!** Deviations really stem from criticality.

¹Gazdzicki, Seyboth, APP '15; E. Andronov, 1610.05569; A. Seryakov, 1704.00751

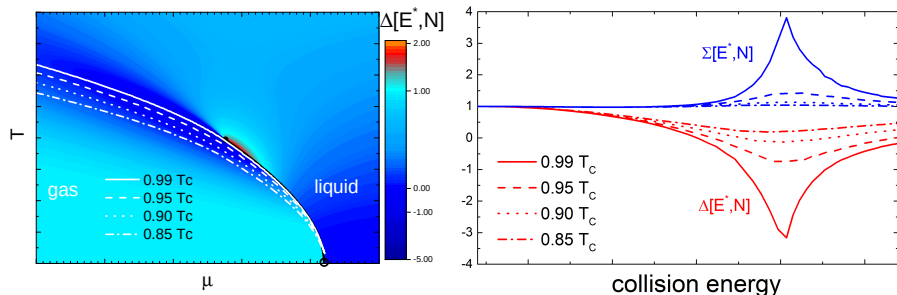
²V.V., Poberezhnyuk, Anchishkin, Gorenstein, J. Phys. A 49, 015003 (2016)

Strongly intensive measures in T - μ plane: Nuclear matter



- Both $\Delta[E^*, N]$ and $\Sigma[E^*, N]$ signal nuclear liquid-gas criticality
- $\Sigma[E^*, N] > 0$ always. However, $\Delta[E^*, N]$ can be both positive and negative

Strongly intensive measures in T - μ plane: Nuclear matter

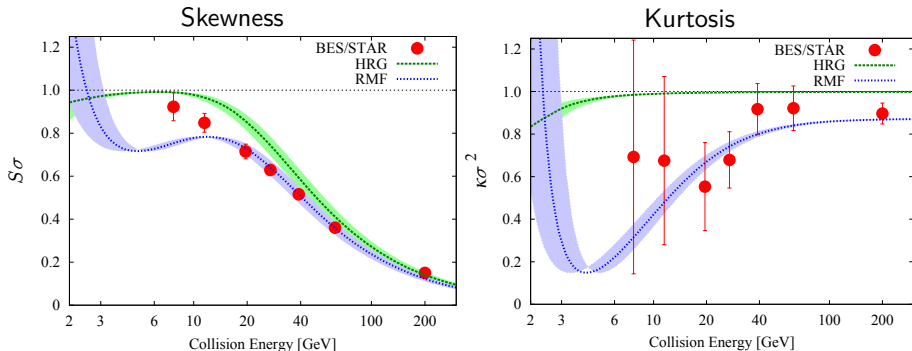


- Both $\Delta[E^*, N]$ and $\Sigma[E^*, N]$ signal nuclear liquid-gas criticality
- $\Sigma[E^*, N] > 0$ always. However, $\Delta[E^*, N]$ can be both positive and negative
- Non-monotonous energy/system-size dependence of $\Delta[E^*, N]$ and $\Sigma[E^*, N]$ in a scenario with CP
- $\Delta[E^*, N]$ is more sensitive than $\Sigma[E^*, N]$ to proximity of CP

Net-baryon fluctuations and nuclear matter

Are NN interactions relevant for heavy-ion collisions?

Net-nucleon fluctuations within RMF (σ - ω model) of nuclear matter along line of “chemical freeze-out”

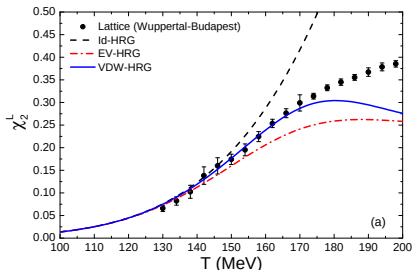


A notable effect in fluctuations even at $\mu_B \simeq 0$

Reconciliation of HRG with nuclear matter can be interesting

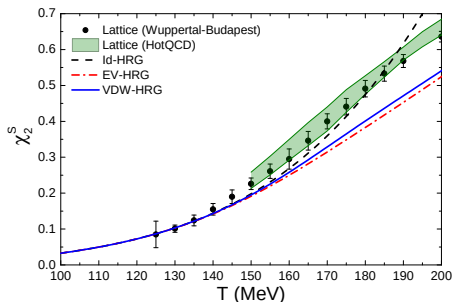
K. Fukushima, PRC 91, 044910 (2015)

VDW-HRG at $\mu = 0$: net-light and net-strangeness



- Net-strangeness χ_2^S
- Underestimated by HRG models, similar for χ_{11}^{BS}
- Extra strange states?¹
- Weaker VDW interactions for strange baryons?²

- Net number of **light quarks** χ_2^L
- $L = (u + d)/2 = (3B + S)/2$
- **Improved** description in VDW-HRG



¹Bazavov et al., PRL 113, 072001 (2014)

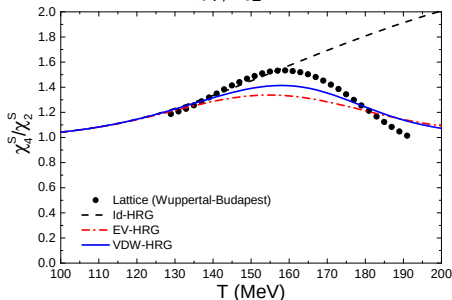
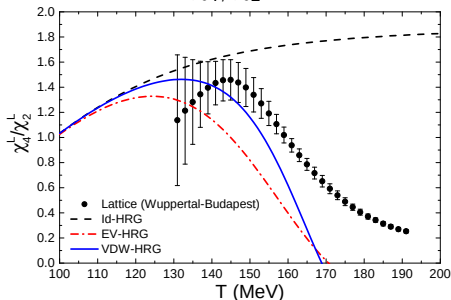
²Alba, Vovchenko, Gorenstein, Stoecker, arXiv:1606.06542

VDW-HRG at $\mu_B = 0$: net-light and net-strangeness

Fluctuations of **net-light** $L = (u + d)/2 = (3B + S)/2$ and **net-strangeness**

$$\chi_4^L/\chi_2^L$$

$$\chi_4^S/\chi_2^S$$



- Lattice shows **peaked structures** in crossover regions
- Not at all reproduced by Id-HRG, signal for deconfinement?¹
- **Peaks** at different T for net-L and net-S $\Rightarrow$ **flavor hierarchy?**²
- VDW-HRG **also shows** peaks and flavor hierarchy $\Rightarrow$ cannot be traced back directly to deconfinement

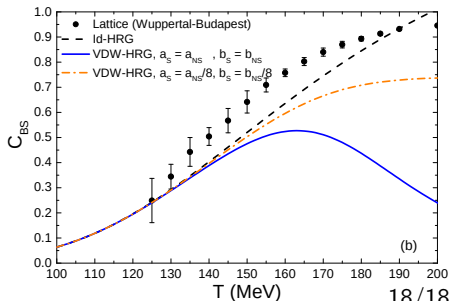
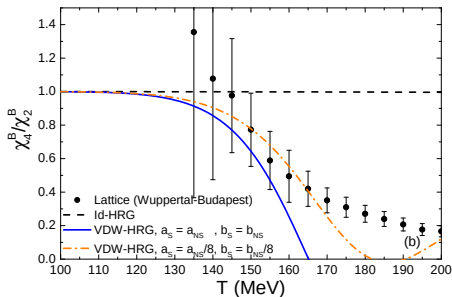
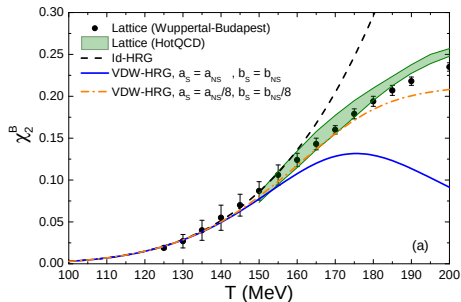
¹S. Ejiri, F. Karsch, K. Redlich, PLB 633, 275 (2006)

²Bellwied et al., PRL 111, 202302 (2013)

VDW-HRG: extensions

Effect of reducing VDW interactions involving strange baryons

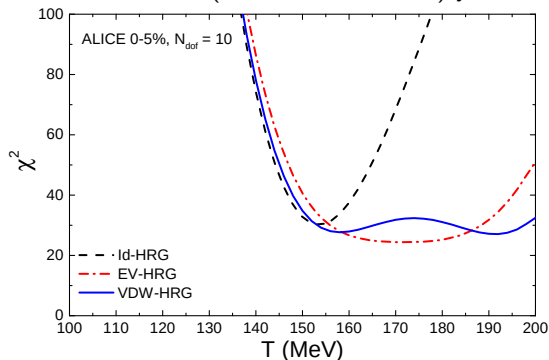
- twice smaller radius for strange baryons
- Illustrative calculation
- Most observables improved



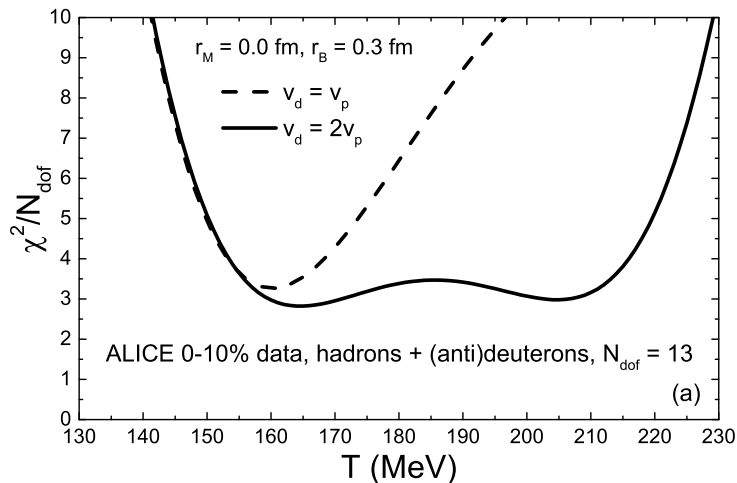
VDW-HRG: influence on hadron ratios

VDW interactions **change** relative **hadron yields** in HRG

Thermal model fit to **ALICE** (Pb+Pb @ 2.76 TeV) yields: from π to Ω



- Fit quality slightly **better** in EV-HRG/VDW-HRG vs Id-HRG but very **different picture!**
- **All** temperatures between 150 and 200 MeV yield similarly **fair** data description in VDW-HRG
- Results likely to be **sensitive** to further **modifications**, e.g for **strangeness**



- Picture changes dramatically when changing deuteron eigenvolume to two times the proton one