Analysis of hadron yield data within HRG model with multi-component eigenvolume corrections

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based on arXiv:1512.08046 and arXiv:1606.06218

Strangeness in Quark Matter 2016

Berkeley, USA

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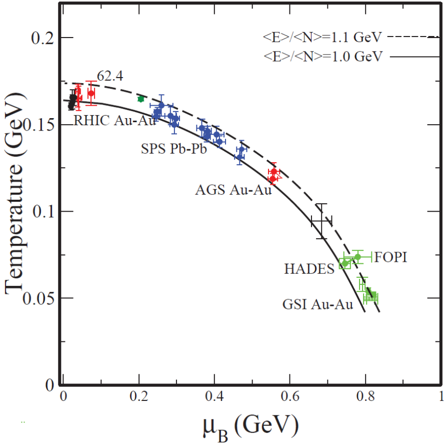
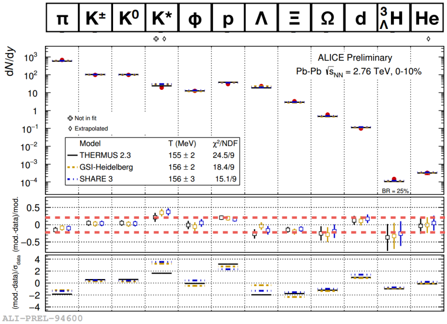
Freeze-out parameters from χ^2 fits within HRG model

Cleymans et al. PRC (2006); Andronic et al. NPA (2006); Becattini et al. PRC (2006).



ALICE Pb+Pb $\sqrt{s_{NN}} = 2.76$ TeV



ALICE Collab., SQM2015, QM2015

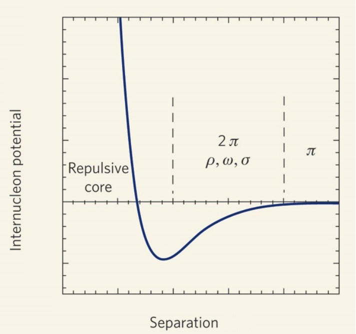
Chemical freeze-out in HIC mapped on QCD phase diagram but ...

- How robust are the conclusions based on ideal gas?
- Is there really a sharp freeze-out with well-defined temperature?

Interacting hadron gas

- In realistic hadron gas there are attractive and repulsive interactions
- Attraction already included by resonances
- Model repulsive interactions by eigenvolume correction
- Van der Waals procedure: $V \to V - vN$

$$P = \frac{NT}{V - vN}$$



In GCE: transcendental equation for pressure[1]

$$P(T,\mu) = P^{\rm id}(T, \mu - v\,P), \qquad n(T,\mu) = n^{\rm id}(T,\mu^*)/(1 + v\,n^{\rm id}(T,\mu^*))$$

In multi-component system $V \to V - \sum_i v_i\,N_i$ ("Diagonal" EV model)[2]

$$P(T,\mu) = \sum_i P_i^{\rm id}(T, \mu_i - v_i\,P), \qquad n_i(T,\mu) = n_i^{\rm id}(T,\mu_i^*)/(1 + \sum_i v_i\,n_i^{\rm id}(T,\mu_i^*))$$

[1] D.H. Rischke, M.I. Gorenstein, H. Stoecker, W. Greiner, Z.Phys. C 51, 485 (1991)
[2] G.D. Yen, M.I. Gorenstein, W. Greiner, S.N. Yang, Phys. Rev. C 56, 2210 (1997)

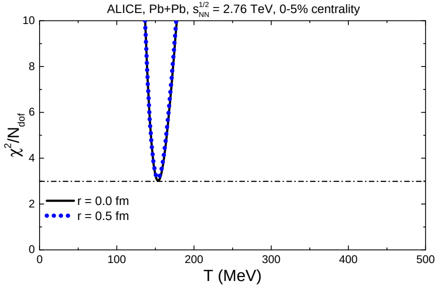
Eigenvolumes: Scenario 0

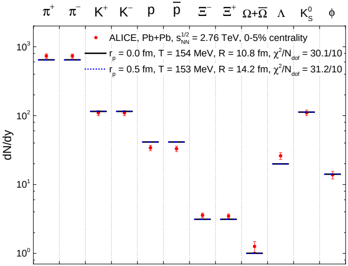
How to choose eigenvolumes for different hadrons?
Not many constraints $\Rightarrow$ consider different scenarios

Scenario 0: Constant eigenvolume for all hadrons ($v_i \equiv v$)

In this case in Boltzmann approximation

$$n_i(T,\mu) = \frac{n_i^{\rm id}(T,\mu_i)\, e^{-vP/T}}{1+\sum_i v\, n_i^{\rm id}(T,\mu_i)\, e^{-vP/T}} \qquad \text{and} \qquad \frac{n_i(T,\mu)}{n_j(T,\mu)} = \frac{n_i^{\rm id}(T,\mu)}{n_j^{\rm id}(T,\mu)}$$

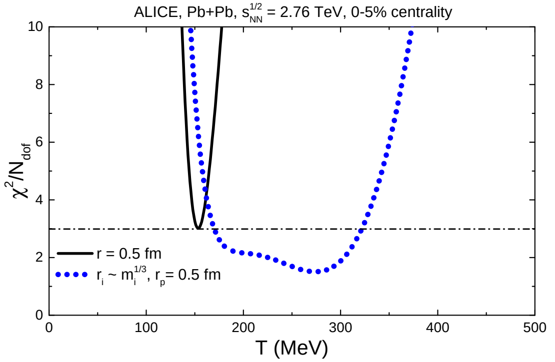




- Simplest and most commonly used parametrization
- Eigenvolume effects essentially cancel out in yield ratios
- No change in T or μ_B compared to point-particle case

Scenario 1: Mass-proportional eigenvolumes ($v_i = m_i/\varepsilon_0$ or $r_i \sim m_i^{1/3})^3$

- Bag model inspired
- Obtained originally for heavy Hagedorn states
- Results in stronger suppression of heavier hadrons



Drastic changes in ALICE χ^2 profile, also high sensitivity on ε_0

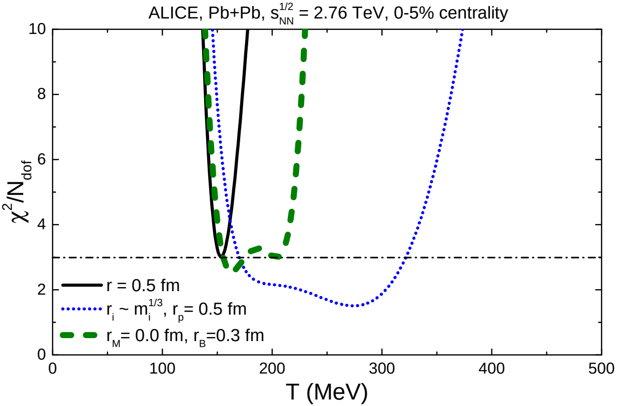
For $r_p = 0.5$ fm global minimum at $T \simeq 270$ MeV

[3] Hagedorn, Rafelski, Phys. Lett. B (1980); Kapusta, Olive, Nucl. Phys. A (1983)

Eigenvolumes: Scenario 2

Scenario 2: Two-component model: different volumes for mesons and baryons

We consider particular case $r_M = 0$ and $r_B = 0.3$ fm,
has been compared to lattice successfully[4]



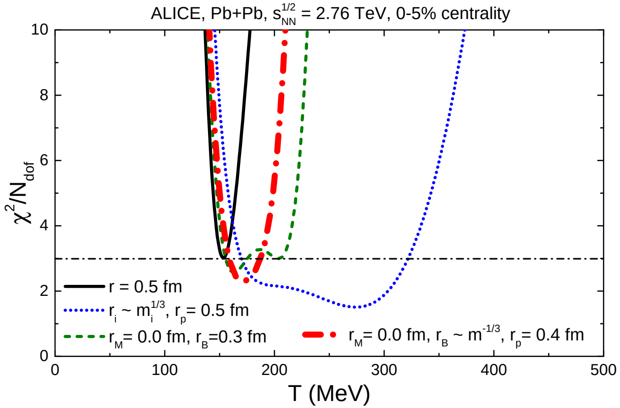
Wide irregular minimum in $T = 155 - 210$ MeV range

[4] A. Andronic, P. Braun-Munzinger, J. Stachel, M. Winn, Phys. Lett. B 718, 80 (2012).

Eigenvolumes: Scenario 3

Scenario 3: Point-like mesons and reverse bag model for baryons $v_B \sim 1/m$

Strange baryons have generally smaller volumes than non-strange ones



Result: $T_{ch} = 175 \pm 20$ MeV

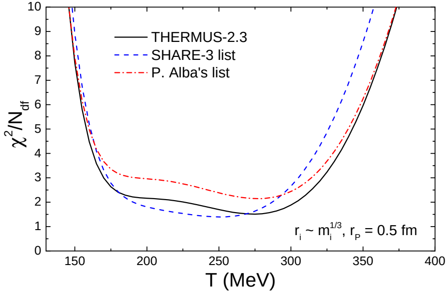
Many other options possible...

Dependence on particle list and decay branching ratios

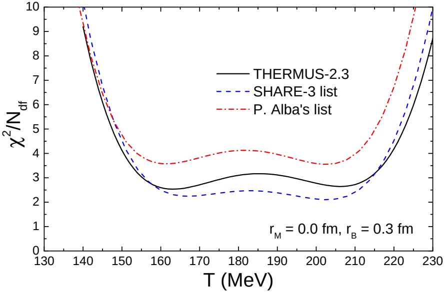
Thermal fits may be sensitive to input particle list

Cross-check: THERMUS-2.3 and SHARE-3.0 (publicly available), and list from P. Alba which includes many unconfirmed states

$r_i \sim m_i^{1/3}, r_p = 0.5$ fm



$r_M = 0, r_B = 0.3$ fm



χ^2 profile shape is rather insensitive to details of particle list

Picture can be more complicated if light nuclei are considered

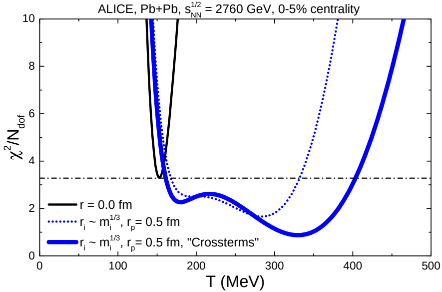
Crossterms eigenvolume model

The "Diagonal" EV model we used is not perfectly consistent with virial expansion for multi-component system of hard spheres

$$P(T,\{n_i\}) = T\sum_i n_i + \sum_{ij} b_{ij} n_i n_j + \ldots \quad \text{with} \quad b_{ij} = \frac{2\pi}{3}(r_i + r_j)^3$$

On the other hand, the "Crossterms" eigenvolume model is[5]

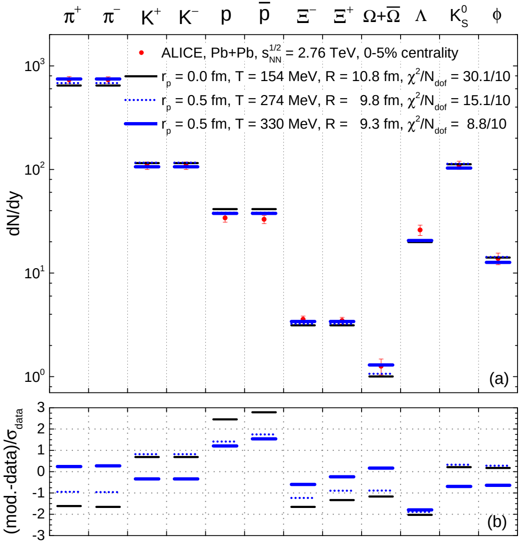
$$P(T,\{n_i\}) = T\sum_i \frac{n_i}{1 - \sum_j v_j n_j}, \quad \Rightarrow \quad P(T,\{n_i\}) = T\sum_i \frac{n_i}{1 - \sum_j \tilde{b}_{ji} n_j},$$



- Scenario 1: $r_i \sim m_i^{1/3}$
- "Crossterms" give even stronger effect
- $\chi^2/N_{\rm df}$: $30/10 \to 15/10 \to 9/10$
- $T_{\rm ch}$: $155 \to 270 \to 320$ MeV

[5] M.I. Gorenstein, A.P. Kostyuk, Ya.D. Krivenko, J. Phys. G 25, L75 (1999)

ALICE yields within bag-like eigenvolume parametrization



χ^2 profile at lower energies

So what about other experiments at lower collision energies?

Finite net-baryon density $\Rightarrow$ additional fit parameter μ_B

Fits to NA49 Pb+Pb 4π data at $\sqrt{s_{\rm NN}} = 6.3, 7.6, 8.8, 12.3$, and 17.3 GeV, and STAR Au+Au dN/dy data at $\sqrt{s_{\rm NN}} = 200$ GeV

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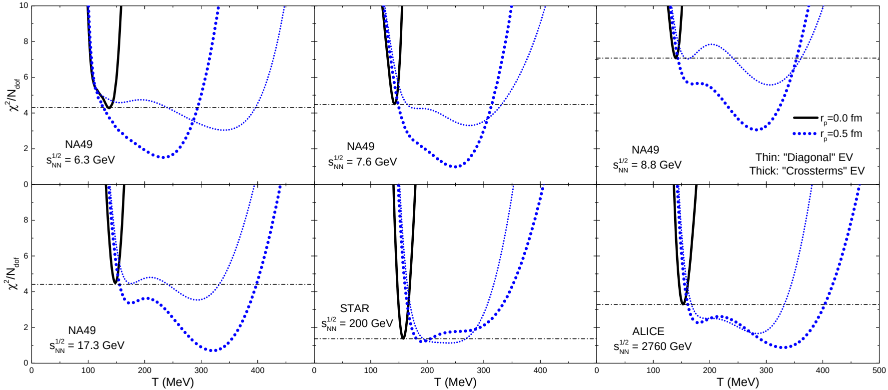
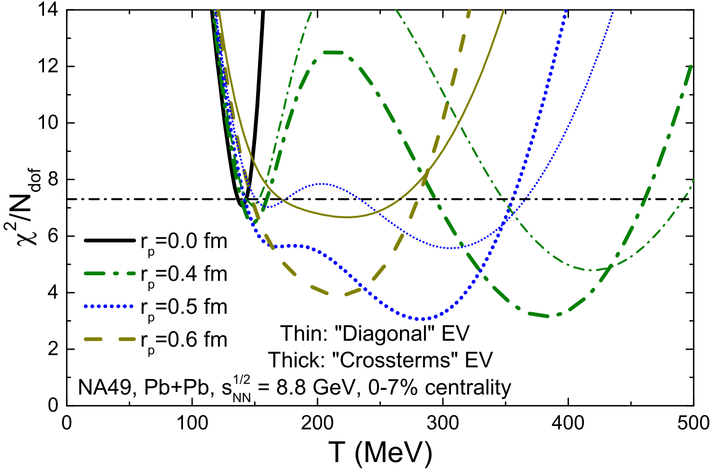
"Crossterms" model with $r_i = r_p\,(m_i/m_p)^{1/3}$ and $r_p = 0.5$ fm



All the same effect, improved χ^2, huge sensitivity

χ^2 profile at lower energies

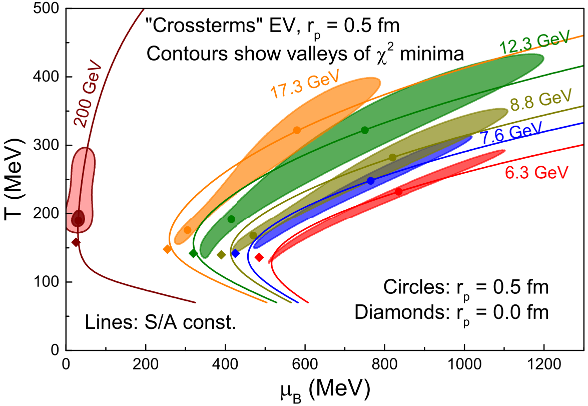
"Crossterms" model with $r_i = r_p \, (m_i/m_p)^{1/3}$ and $r_p = 0.4, 0.5, 0.6$ fm



Huge sensitivity on r_p

χ^2 in T-μ_B plane

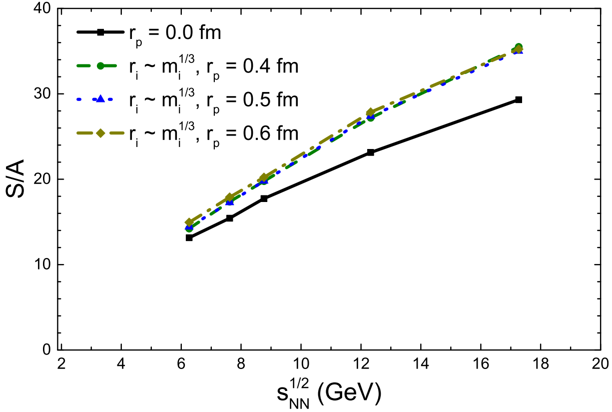
The T-μ_B dependence gives a more complete picture



- Conclusions based on point-particle HRG are not robust
- T and μ_B are clearly correlated
- Entropy per baryon S/B approx. constant along valleys of χ^2 minima
- Compatible with isentropic expansion and continuous freeze-out?

Entropy per baryon

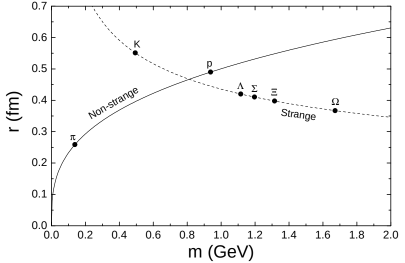
Entropy per baryon excitation function



- S/A at global minima are same for different finite values of r_p
- Entropy per baryon is a robust observable
- On the other hand E/N is NOT constant, 1.2-1.5 GeV in EV-HRG
- Interpretation of results prone to controversy, needs further studies

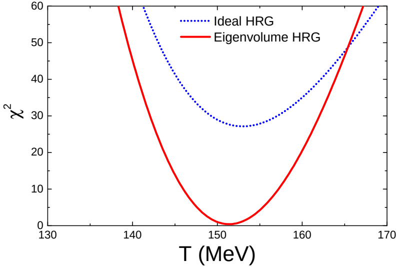
Flavor-dependent eigenvolumes

Next step: different eigenvolumes for strange and non-strange hadrons



- Smaller volumes for strange particles
- Non-strange: $v_i \sim m_i$
- Strange: $v_i \sim 1/m_i$ (reverse!)
- Normalization from best fit to ALICE data

- $\chi^2/N_{\rm dof}$: 27.1/8 → 0.42/6
- Remarkably small χ^2
- No dramatic change in T
- Same for all other centralities



P. Alba, V. Vovchenko, M.I. Gorenstein, H. Stoecker, arXiv:1606.06542

Summary

- Thermal fits are extremely sensitive to eigenvolume interactions
- Chemical freeze-out parameter values from ideal HRG are not unique
- Entropy per baryon is a robust observable, E/N is not
- Mass-proportional eigenvolumes improve agreement with data and lead to generally wider and irregular χ^2 minima. Obtained results hint on isentropic expansion and continuous chemical freeze-out
- Flavor-dependent eigenvolumes lead to essential improvement with data
- Proper restrictions on eigenvolumes are really needed!

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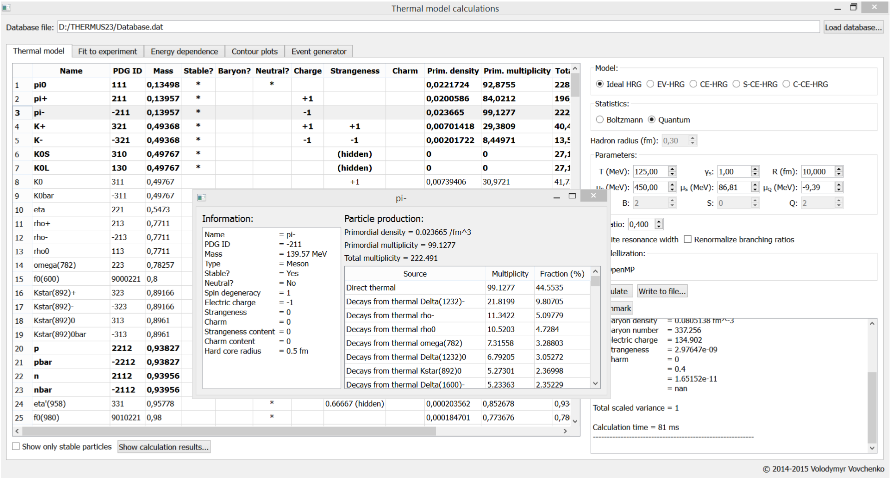
Thanks for your attention!

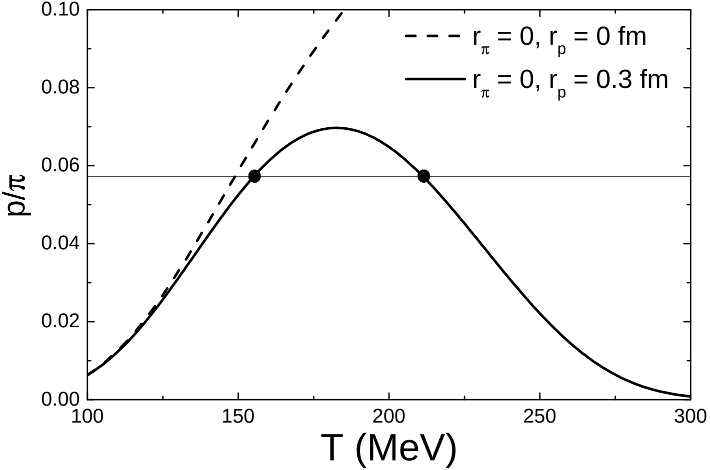
Backup slides

Some details about implementation

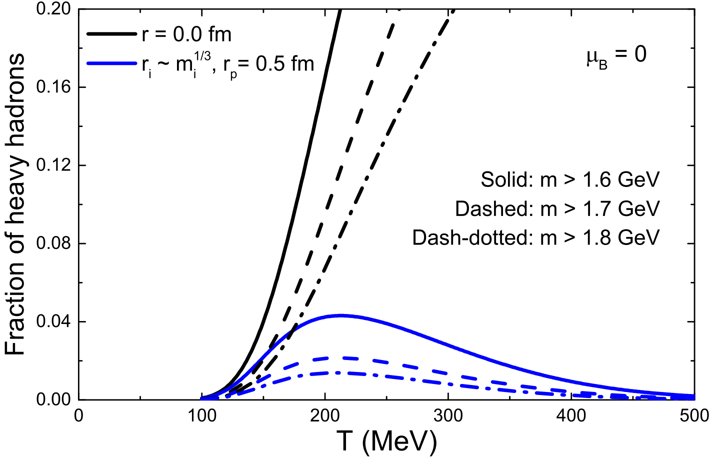
- Own implementation of eigenvolume HRG written in C++ is used
- Solves eigenvolume models, also many other features
- Auxiliary tool: GUI written within Qt framework
- Where possible cross-checked with other codes



Origin of two local minima: non-monotonic dependence of individual ratios due to eigenvolumes



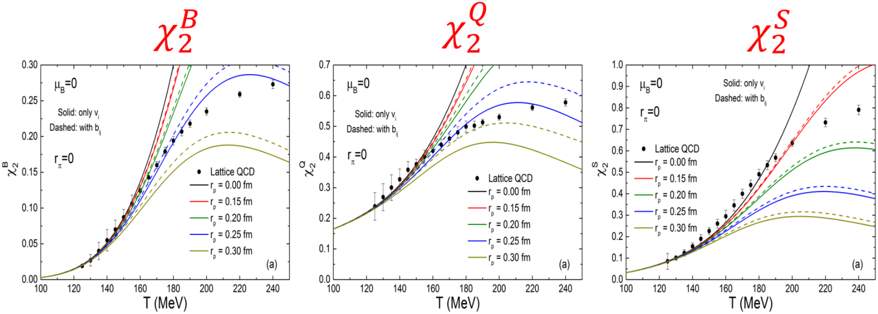
Heavy baryons contribution



Hagedorn divergences are tamed within eigenvolume model

Limiting temperature may be artefact of using point-particle gas

Susceptibilities in eigenvolume HRG



Strangeness susceptibility behave differently from baryon and electric charge

Hint at flavor dependence of eigenvolumes?