Multiplicities of light nuclear clusters in high energy nuclear collisions and solution of the hyper-triton puzzle

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Outline

1. Motivation and introduction
2. Old and new versions of hadron resonance gas model (HRGM)
3. Fixing hard-core radii from not LHC data
4. What are the hard-core radii of (anti)nuclei
5. Single or separate chemical freeze-out of hadrons or nuclei
6. Conclusions

Major Aims of Experiments on A+A Collisions

Study the QCD phase diagram:

1. **detect signals of colour deconfinement;**
2. **detect signals of (partial) chiral symmetry restoration;**
3. **locate (tri)critical endpoint(s) of QCD phase diagram.**

In order to resolve these tasks we need
a very good tool to analyze the data!

Works on new HRGM

During 2013-2017 our group developed a very accurate tool to analyze data

D. Oliinychenko, KAB, A. Sorin, Ukr. J. Phys. 58 (2013)

KAB, D. Oliinychenko, A. Sorin, G.Zinovjev, EPJ A 49 (2013)

KAB et al., Europhys. Lett. 104 (2013)

KAB et al., Nucl. Phys. A 970 (2018)

Most successful version of the Hadron Resonance Gas Model (HRGM)

The high quality description of data allowed us to elucidate new irregularities at CFO from data and to formulate new signals of two QCD phase transitions

D. Oliinychenko et al., Ukr. J Phys. 59 (2014)

KAB et al., Phys. Part. Nucl. Lett. 12 (2015)

KAB et al., EPJ A 52 (2016) No 6

KAB et al., EPJ A 52 (2016) No 8

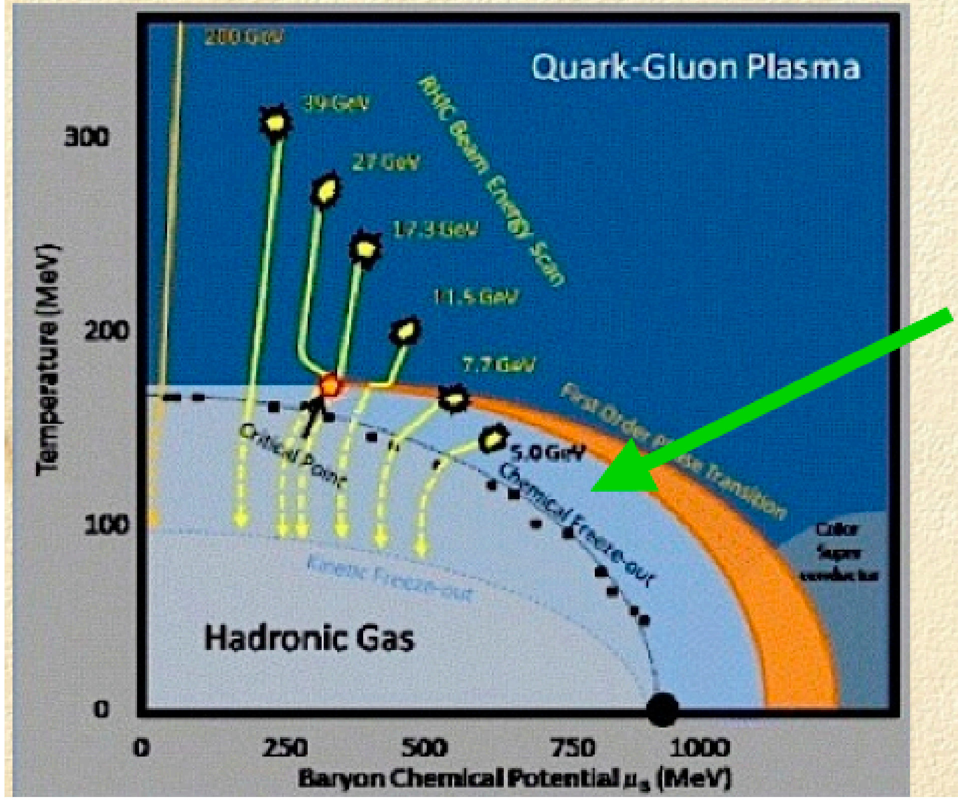
KAB et al., Phys. Part. Nucl. Lett. 15 (2018)

First work on evidence of two QCD phase transitions

HRG: a Multi-component Model

HRG model is a truncated Statistical Bootstrap Model with the excluded volume correction a la VdWaals for all hadrons and resonances known from Particle Data Group.

For given temperature T, baryonic chem. potential, strange charge chem. potential, chem. potential of isospin 3-rd projection => thermodynamic quantities => all charge densities, to fit data.



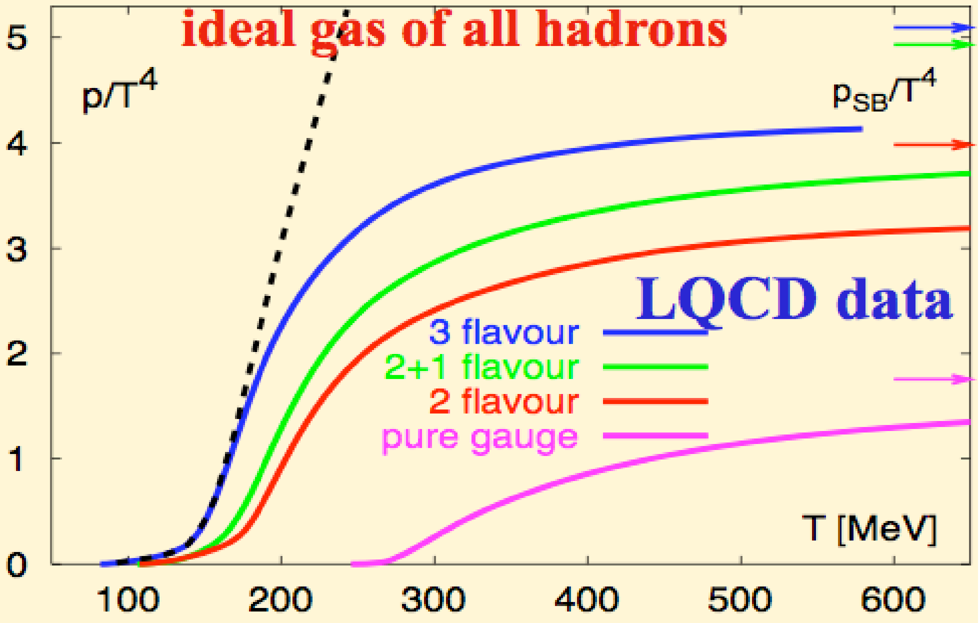
Chemical freeze-out - moment after which hadronic composition is fixed and only strong decays are possible. I.e. there are no inelastic reactions.

Why Van der Waals or Hard-core Repulsion EoS?

1. Hard-core repulsion EoS (= VdWaals without attraction) has the same energy per particle as an ideal gas => there is no problems to convert its energy into ideal gas energy

Proof: if particles stay apart, they do not interact, if particles touch each other, potential energy is infinite and => such configurations do not contribute into partition

2. Hard-core repulsion does not create problems with QGP existence, since such repulsion suppresses pressure compared to ideal gas EoS



Why Van der Waals or Hard-core Repulsion EoS?

3. Almost in the whole hadronic phase the mixture of stable hadrons and resonances behaves as a mixture of ideal gases with small hard-core radii

due to approximate cancellation of attraction and repulsion terms among the quantum second virial coefficients of hadrons

R. Venugopalan and M. Prakash, Thermal properties of interacting hadrons.
***Nucl. Phys. A* 1992, *546*, 718**

HRG: a Multi-component Model

Traditional HRG model: one hard-core radius R=0.25-0.3 fm

A. Andronic, P.Braun-Munzinger, J. Stachel, NPA (2006)777

Overall description of data (mid-rapidity or 4π multiplicities) is good!

But there are problems with K+/pi+ and Λ/pi- ratios at SPS energies!!! => Two component model was suggested

HRG: a Multi-component Model

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A. Andronic, P.Braun-Munzinger, J. Stachel, NPA (2006)777

Overall description of data (mid-rapidity or 4π multiplicities) is good!

Two hard-core radii: R_pi =0.62 fm, R_other = 0.8 fm

G. D. Yen. M. Gorenstein, W. Greiner, S.N. Yang, PRC (1997)56

Or: R_mesons =0.25 fm, R_baryons = 0.3 fm

A. Andronic, P.Braun-Munzinger, J. Stachel, NPA (2006) 777 PLB (2009) 673

Two component models do not solve the problems!

Hence we need more sophisticated approach.

HRG: a Multi-component Model

Severe problems with light nuclei

- On the one hand, the light nuclei yields maybe very sensitive to the properties of the phase in which they are formed
- On the other hand, the quantum second virial coefficients of nuclei and hadrons are not known…
- Even the classical second virial coefficients (excluded volume) of nuclei and hadrons were found very recently only!

  See KAB et al, arXiv:2005.01555v1 [nucl-th]
- After finding the excluded volumes one has to reformulate the HRGM completely, since the number of virial coeffieints is (Number of nuclei) x (number of hadronic hard-core radii)!
- => There is no alternative to the classical approach!

Wide Resonances Are Important

The resonance width is taken into account in thermal densities.

In contrast to many other groups we found that
wide resonances are VERY important in a thermal model.
For instance, description of pions cannot be achieved without

σ meson: $m_\sigma = 484 \pm 24$ MeV, width $\Gamma_\sigma = 510 \pm 20$ MeV

R. Garcia-Martin, J. R. Pelaez and F. J. Yndurain, PRD (2007) 76

$$n_X^{tot} = n_X^{thermal} + n_X^{decay} = n_X^{th} + \sum_Y n_Y^{th}\, Br(Y \to X)$$

$Br(Y \to X)$ is decay branching of Y-th hadron into hadron X

From our experience =>

It is more instructive to fit the ratios of yields since the systematic uncertainties cancel!

Data and Fitting Parameters

111 independent hadronic ratios measured at AGS, SPS and RHIC energies

# of published ratios measured at mid-rapidity depends on energy =>

$\sqrt{s_{NN}}$ (GeV)	N_{rat} FO
2.7	4
3.3	5
3.8	5
4.3	5
4.9	8
6.3	9
7.6	10
8.8	11
9.2	5
12	10
17	13
62.4	5
130	11
200	10
Sum	111

# of local fit parameters cannot be larger than 4 (for all energies) or larger than 5 (for energies above 2.7 GeV)

# of local fit parameters for each collision energy = 3 (no γ_S factor)
T, mu_B, mu_I3
Total # for 14 energies = 42

# of fit parameters with γ_S factor is 4
Total # for 14 energies = 56

# of global fit parameters = 4
R_pi, R_K, R_mesons, R_baryons

Induced Surface Tension EOS

pressure

$$\frac{p}{T} = \sum_i \phi_i \exp\left(\frac{\mu_i - pV_i - \Sigma S_i}{T}\right)$$

induced surface tension

$$\frac{\Sigma}{T} = \sum_i R_i \phi_i \exp\left(\frac{\mu_i - pV_i - \Sigma S_i}{T}\right) \cdot \overbrace{\exp\left(\frac{(1-\alpha) S_i \Sigma}{T}\right)}^{\text{new term}}$$

R_k, V_k and S_k are hard-core radius, eigenvolume and eigensurface of hadron of sort k

Advantages

1. It allows one to go beyond the Van der Waals approximation, since it reproduces 2-nd, 3-rd and 4-th virial coefficients of the gas of hard spheres for $\alpha = 1.245$.

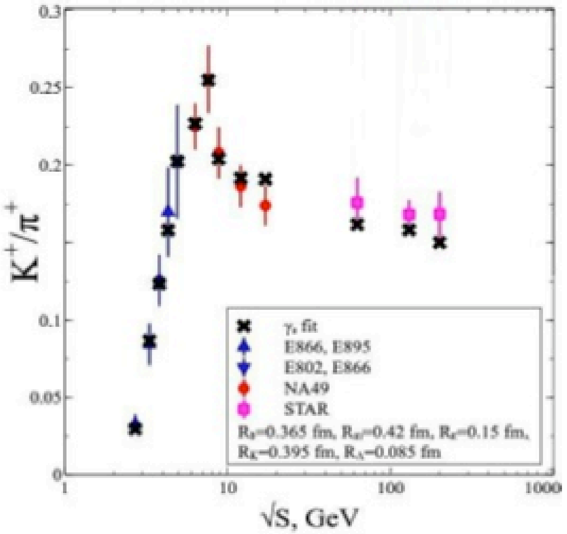
2. Number of equations is 2 and it does not depend on the number of different hard-core radii!

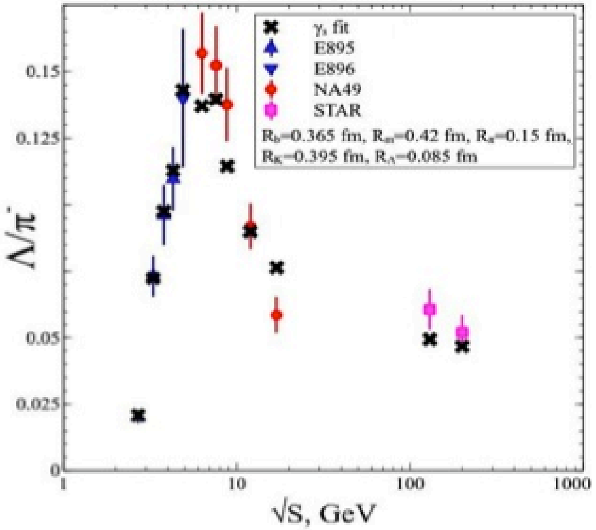
V.V. Sagun, K.A.Bugaev, A.I. Ivanytskyi, D.R. Oliinychenko, EPJ Web Conf 137 (2017);

K.A.Bugaev, V.V. Sagun, A.I. Ivanytskyi, E. G. Nikonov, G.M. Zinovjev et. al., Nucl. Phys. A 970 (2018) 133-155

V.V. Sagun, K.A.Bugaev, A.I. Ivanytskyi, et al., Eur. Phys. J. A 54, 100 (2018).

Most Problematic ratios at AGS, SPS and RHIC energies



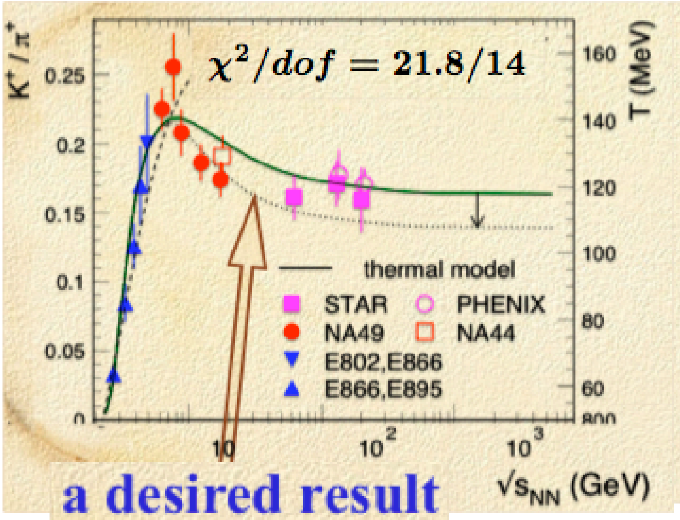


KAB et al., Nucl. Phys. A 970 (2018)

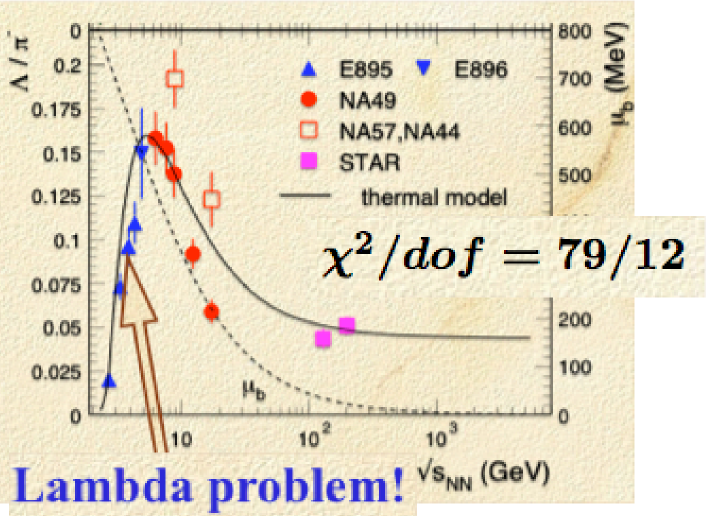
Note: RHIC BES I data have very large error bars and hence, are not analyzed!

IST EOS: $\chi^2/dof \simeq 3.29/14$ $\chi^2/dof \simeq 11.62/12$

Our IST EOS has 3 or 4 more fitting parameters compared to usual HRGM!



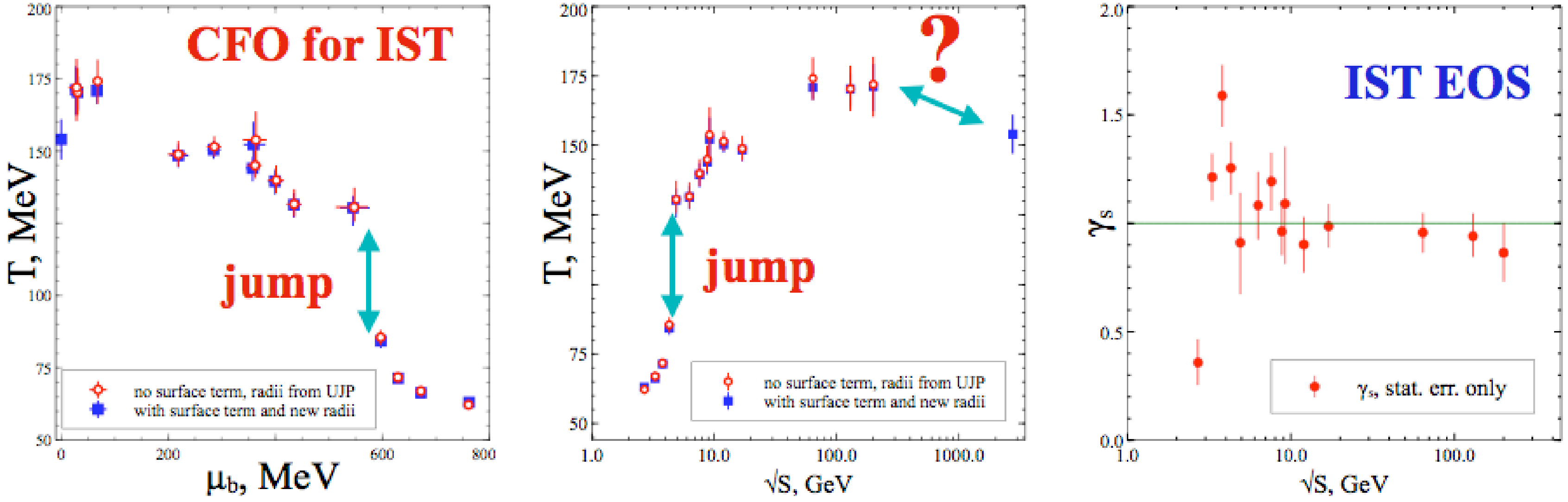
a desired result



Lambda problem!

Conventional one component HRGM by PBM and Co:
A. Andronic, PBM, J. Stachel NPA (2006), PLB (2009)

Main Results for AGS, SPS and RHIC energies



IST EOS (without ALICE):

$$R_\pi=0.15\ \text{fm},\quad R_K=0.395\ \text{fm},\quad R_\Lambda=0.085\ \text{fm},\ R_b=0.365\ \text{fm},\quad R_m=0.42\ \text{fm}$$

Only pion and Λ hyperon radii are changed a bit, but no effect on T and μ_B

1. **We confirm that there is a jump of T_{CFO} between $\sqrt{s}$ = 4.3 GeV and $\sqrt{s}$ = 4.9 GeV**
2. **We confirm that there is a strangeness enhancement peak at $\sqrt{s}$ = 3.8 GeV**
3. **Why Tcfo at LHC is lower than at highest RHIC energy???**

V.V. Sagun et al., NPA (2018) and arXiv:1703.00009 [hep-ph]

ALICE Data on Snowballs in Hell: What are Hard-core Radii of Nuclei?

Main problem with the classical hard-core radius of light nuclei

is that they are clusters itself!

=> No formulas in textbooks on stat.mechanics!

If classical hard-core radii work well for hadrons

=> Classical hard-core radii should work for nuclei

There are 2 distinct cases of clusters:

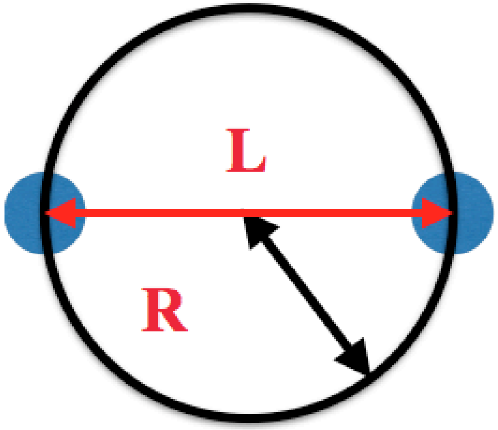
A. tight (=dense) clusters

B. roomy (=empty) clusters

Light Nuclei as Classical Clusters

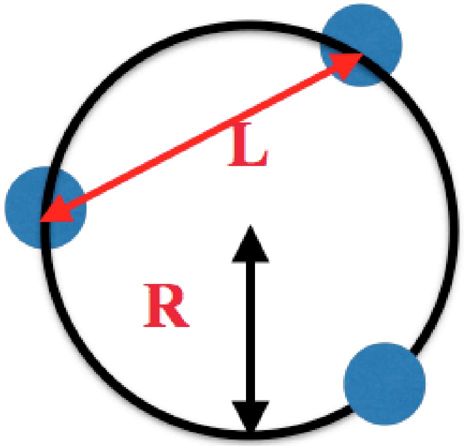
rms = root mean square

nucleus	rms radius (fm)	average distance	(fm)
deuteron	2.1421±0.0088	between particles	4.280
triton	1.7591±0.0363	√3R	3.047
^{3}He	1.9661±0.0030	√3R	3.405
^{4}He	1.6755±0.0028	4R/√6	2.739
${}^{3}_{\Lambda}$H	4.9 (simulations)	~√3R	8.487



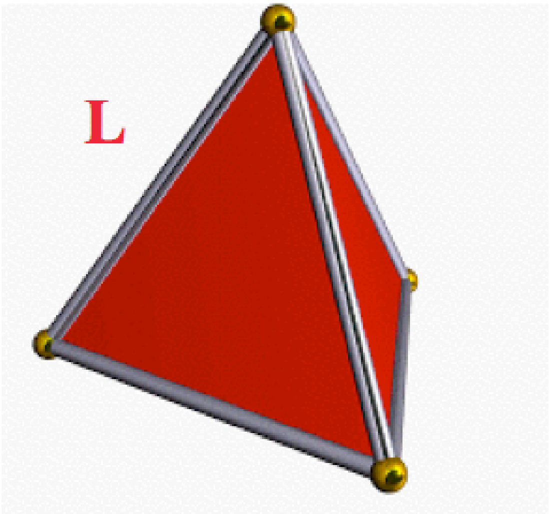
deuteron

L = 2R mean distance



triton, He-3, Hypertriton

L =√3 R



He-4

L =4/√6 R

Classical 2-nd Virial Coefficients of A-nucleons Nuclei and Hadrons

Since A-baryons nuclei are roomy clusters one can FREELY translate

any hadron around each constituent of nuclei $\Rightarrow$

Excluded volume (per particle) of a hadron and nucleus of A baryons is

$$\boldsymbol{b_{Ah} = A\frac{2}{3}\pi(R_b + R_h)^3\,,}$$

R_b is the hard-core radius of baryons

For hyper-triton the formula differs (with R_Λ << R_b)

$$b_{{}^3_\Lambda H\, h} = 2\frac{2}{3}\pi(R_b + R_h)^3 + \frac{2}{3}\pi(R_\Lambda + R_h)^3$$

=> excluded volume of hyper-triton is about the one of d

Excluded volumes of two nuclei AxB can be neglected!

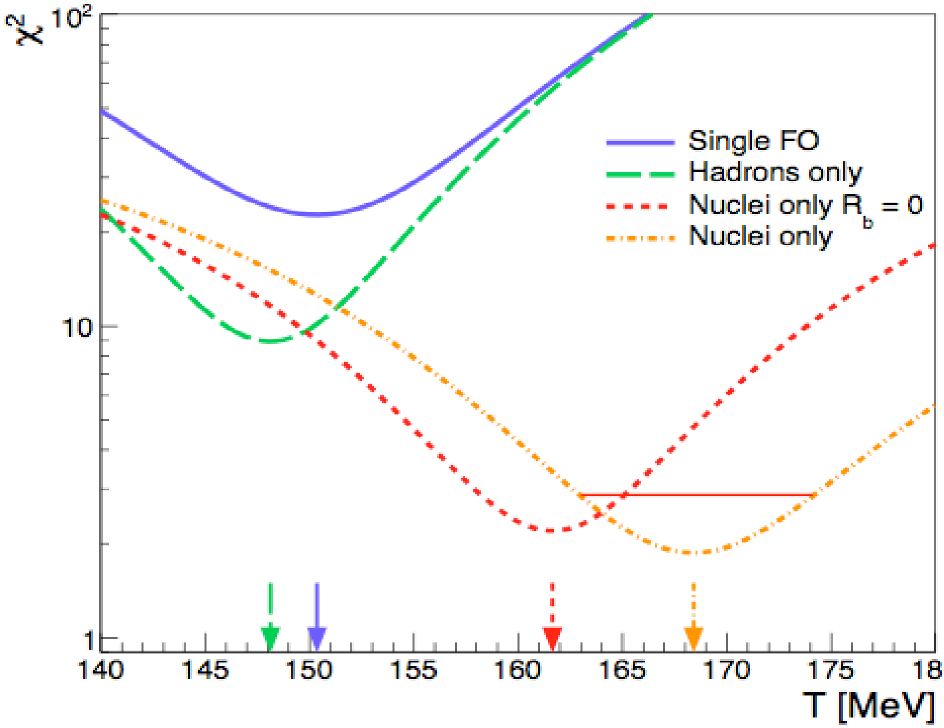
ALICE Data on Snowballs in Hell:
Same CFO of Nuclei and Hadrons

χ^2 has 2 parameters T of all particle and V of nucleons

$$\chi^2_{tot}(V) \;=\; \chi^2_h + \chi^2_A(V) = \sum_{k\in h}\left[\frac{R_k^{theo}-R_k^{exp}}{\delta R_k^{exp}}\right]^2 + \sum_{A}\left[\frac{\rho_A(T)V - N_A^{exp}}{\delta N_A^{exp}}\right]^2$$

1. all loosely bound nuclei are frozen together with hadrons =>

$$T_{CFO} = 150.7 \pm 4\mathrm{MeV} \quad \Rightarrow \quad \chi^2/dof = (9.1+15)/(11+8-2) = 24.1/17 \simeq 1.42$$



minimizing χ^2 with respect to

V of nuclei we find χ^2 (T)

What, if the nuclei

have zero hard-core radius?

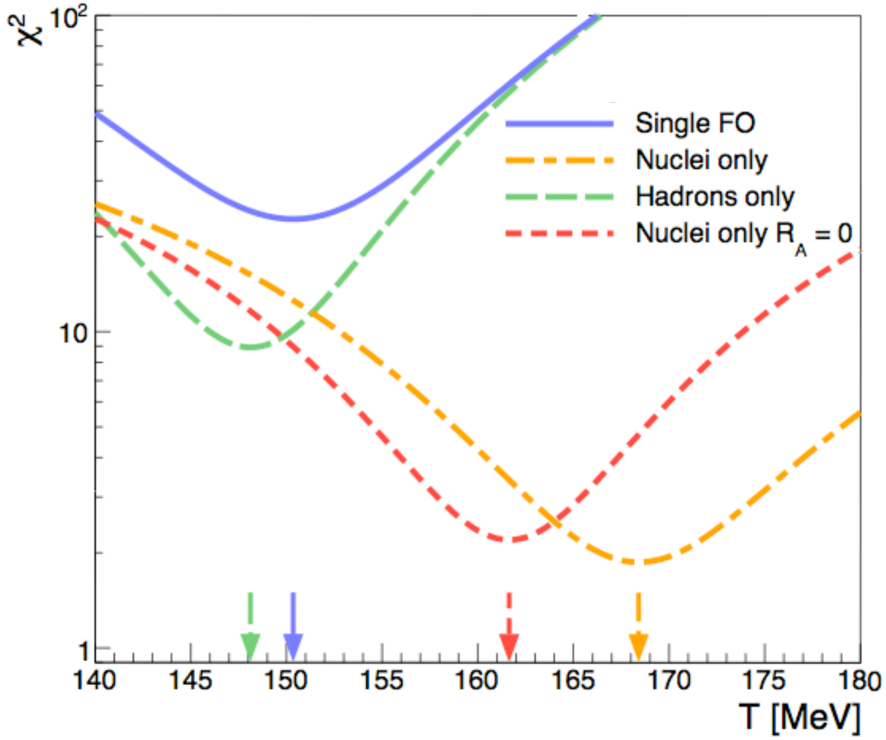
GENERIC:Nuclei prefer higher CFO T

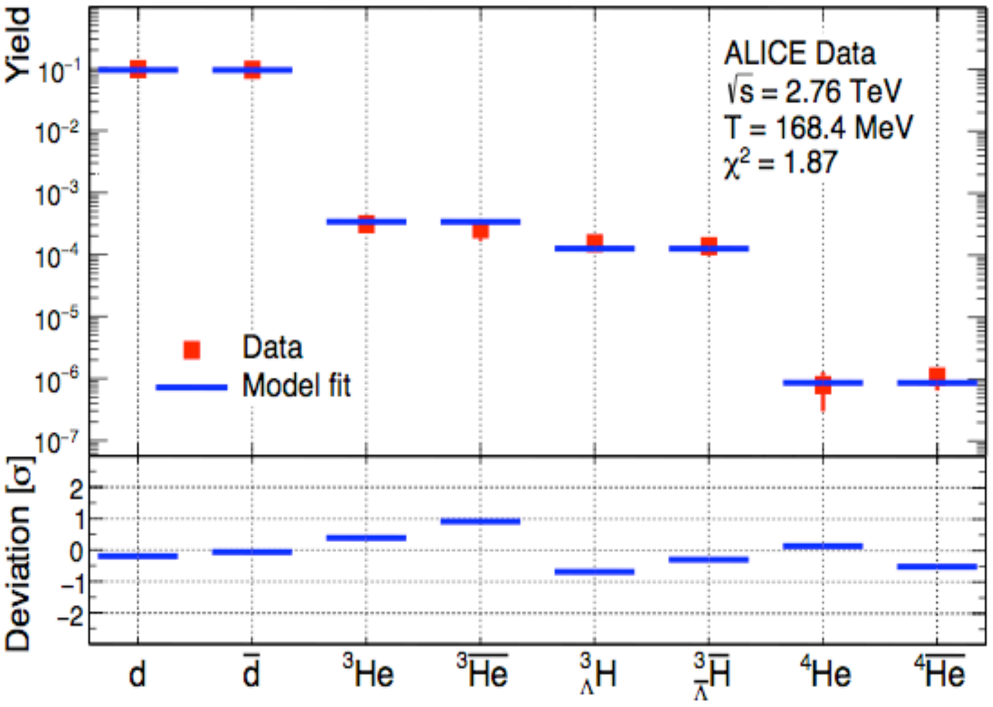
Separate CFO of Nuclei and Hadrons (New)

Now χ^2 has 3 parameters T of hadrons, and V and T of nuclei

$$\chi^2_{tot}(V) \;=\; \chi^2_h + \chi^2_A(V) = \sum_{k\in h}\left[\frac{R_k^{theo} - R_k^{exp}}{\delta R_k^{exp}}\right]^2 + \sum_A \left[\frac{\rho_A(T)V - N_A^{exp}}{\delta N_A^{exp}}\right]^2$$

$T_A = 168.4{-}5.4{+}6 \qquad \chi^2/dof \simeq (9.1{+}1.87)/(11{+}8{-}3) = 10.97/16 \simeq 0.686$

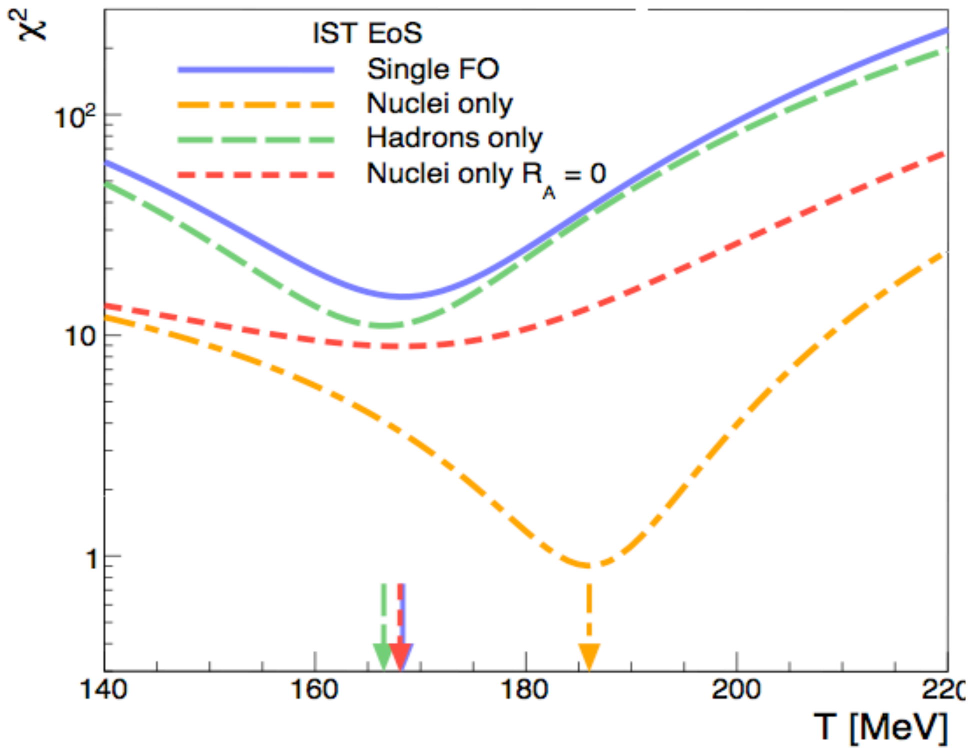


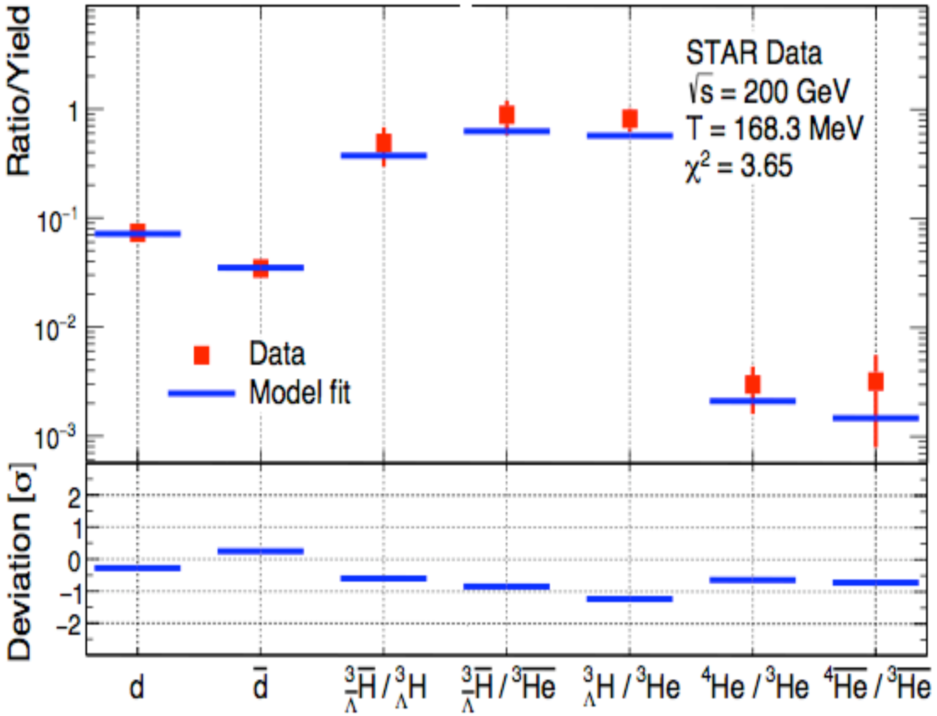


KAB et al, arXiv:2005.01555v1 [nucl-th]

STAR data $\sqrt{s}$ = 200 GeV

We use the same strategy, i.e. verify single CFO vs separate CFO of hadrons and nuclei





Single CFO of hadrons and nuclei at STAR energy is more preferable, since CFO T=191 MeV for nuclei contradicts to lattice QCD data!

The fit quality is χ /dof = 1.07

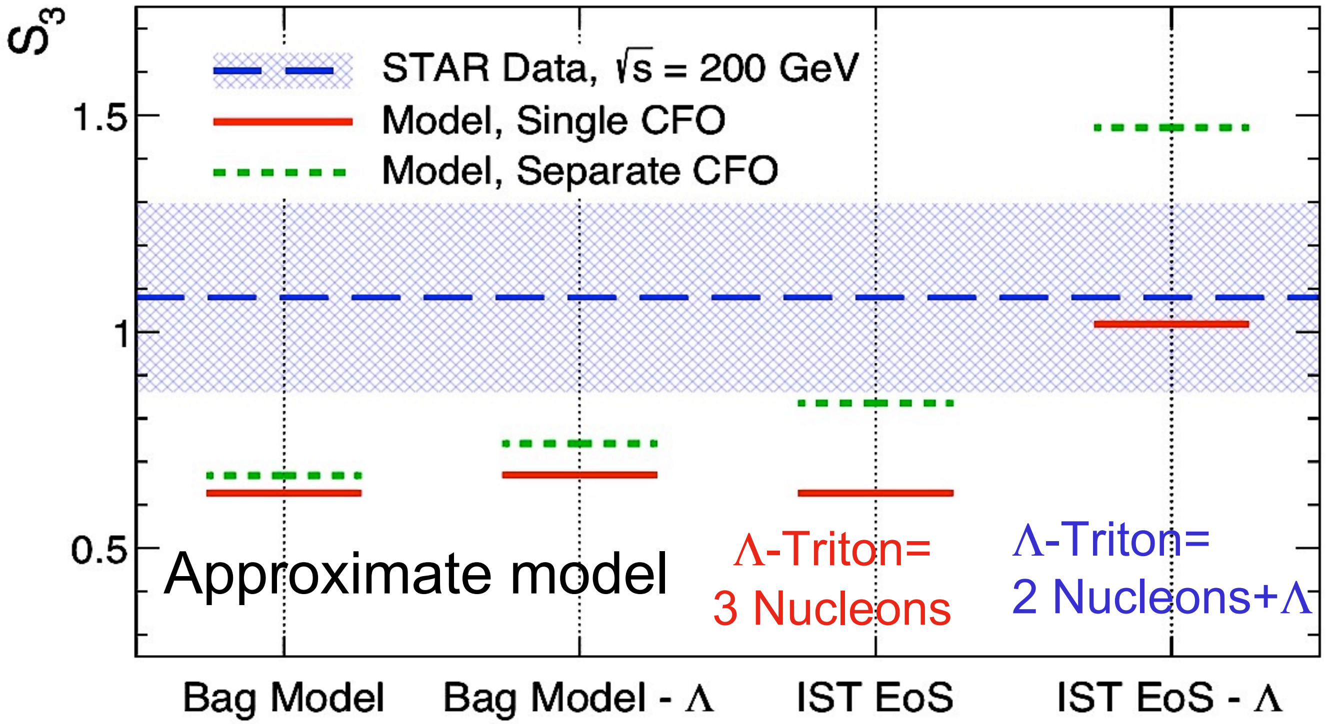
O. Vitiuk, E. Zherebtsova et al., arXiv:2007.07376 [hep-ph]

STAR data $\sqrt{s} = 200$ GeV II

Unexpectedly, the results of fit are extremely sensitive to the excluded volume of hyper-triton!

Taking the Λ hyperon excluded volume found earlier we automatically reproduced (without fitting!) the problematic ratios which include the hyper-triton!

$$S_3 = \frac{{}^3_\Lambda\mathrm{H}}{{}^3\mathrm{He} \times \frac{\Lambda}{p}}, \quad \overline{S}_3 = \frac{{}^3_{\overline{\Lambda}}\overline{\mathrm{H}}}{{}^3\overline{\mathrm{He}} \times \frac{\overline{\Lambda}}{\overline{p}}},$$



Approximate model

Λ-Triton=
3 Nucleons

Λ-Triton=
2 Nucleons+Λ

O. Vitiuk, E. Zherebtsova et al., arXiv:2007.07376 [hep-ph]

Conclusions

The classical 2-nd virial coefficients of light nuclei and hadrons are derived and the IST EoS for the mixture of hadrons and light nuclei is worked out.

On the basis of the IST EoS the hadronic and light nuclei yields measured at ALICE and STAR energies are described with **unprecedented accuracy** χ /dof = 0.7 and χ /dof = 1.07, respectively.

The physics of light nuclei CFO at ALICE and STAR energies seems to be **the same** (T=167-169 MeV), but the physics of hadronic CFO is different (T=150 MeV vs T=168 MeV) at ALICE and STAR energies!

The hypernuclei are extremely sensitive to the excluded volumes of constituents. For the first time we were able to correctly describe S3 and anti-S3 ratios without fitting them, but using the right hard-core radius of Λ **hyperons.**

=> Exotic nuclei can be used to measure the hard-core radii of other hyperons with very high accuracy.

Thank you very much for your attention!