Chemical freeze-out of light nuclei in high energy nuclear collisions and resolution of the hyper-triton chemical freeze-out puzzle

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Moscow, October 8, 2020

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!
- PROBLEM: the STAR data measured in 2011 related to (anti)hyper-triton were never described by HRG or by coalescence models!

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:

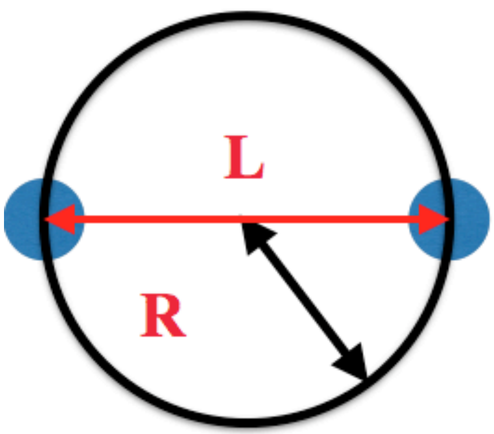
A. tight (=dense) clusters

B. roomy (=empty) clusters

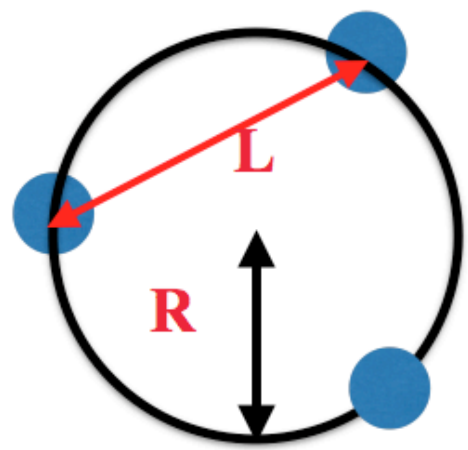
Light Nuclei as Classical Clusters

rms = root mean square

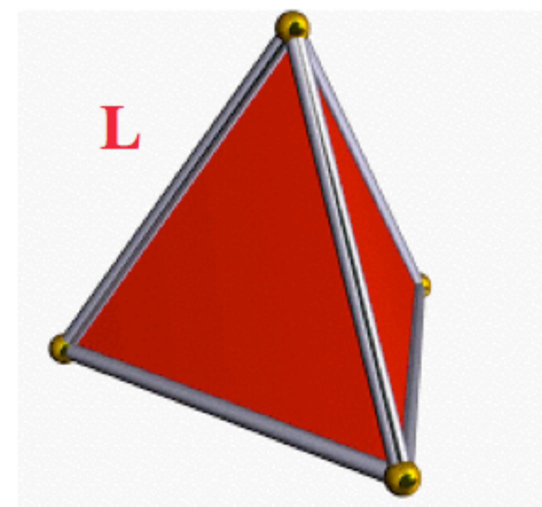
nucleus	rms radius (fm)	average distance between particles	(fm)
deuteron	2.1421±0.0088		4.280
triton	1.7591±0.0363	**√3R**	3.047
^{3}He	1.9661±0.0030	**√3R**	3.405
^{4}He	1.6755±0.0028	**4R/√6**	2.739
$^3_\Lambda$H	4.9 (simulations)	**~√3R**	8.487



deuteron



triton, He-3, Hypertriton



He-4

$L = 2R$ mean distance **$L = \sqrt{3}\,R$** **$L = 4/\sqrt{6}\,R$**

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)

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

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

Excluded volumes of two nuclei AxB can be neglected!

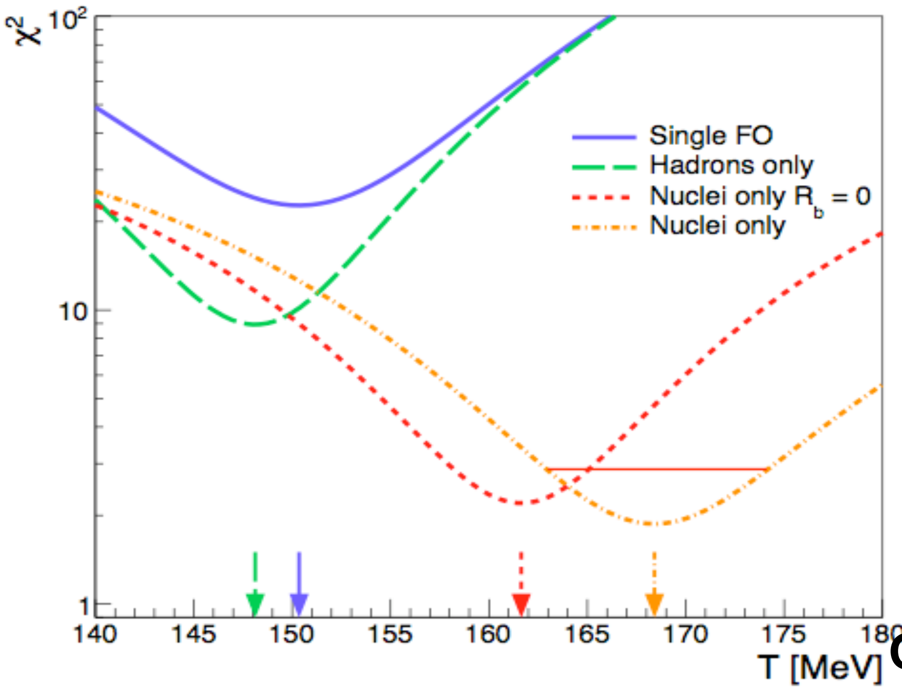
ALICE Data on Snowballs in Hell:
Same CFO of Nuclei and Hadrons

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

ALICE Data on Snowballs in Hell: Same CFO of Nuclei and Hadrons 2

K. A. Bugaev et al.: Second virial coefficients of light nuclear clusters ...

	Description	T_h, MeV	T_A, MeV	V_A, fm^3	χ^2/dof
Approximate	Single CFO, BMR	150.35 ± 1.91	150.35 ± 1.91	11241 ± 2016	1.336
Exact	Single CFO, IST	150.06 ± 1.94	150.06 ± 1.94	13357 ± 2277	1.627

- Internal problem: for same CFO temperature

$$\min\{V_A\} = 11100 \text{ fm}^3 > \max\{V_h\} = 8765 \text{ fm}^3$$

=> For same CFO T the (anti-,hyper-)nuclei are frozen out on a different hyper-surface!

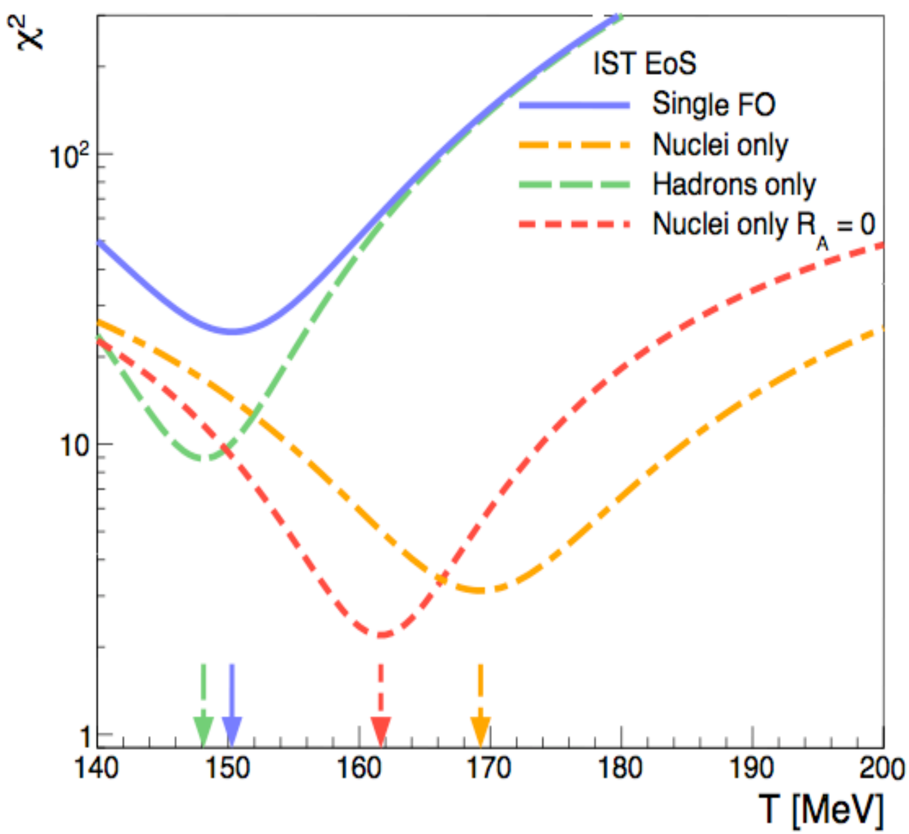
=> A different CFO scenario is necessary!

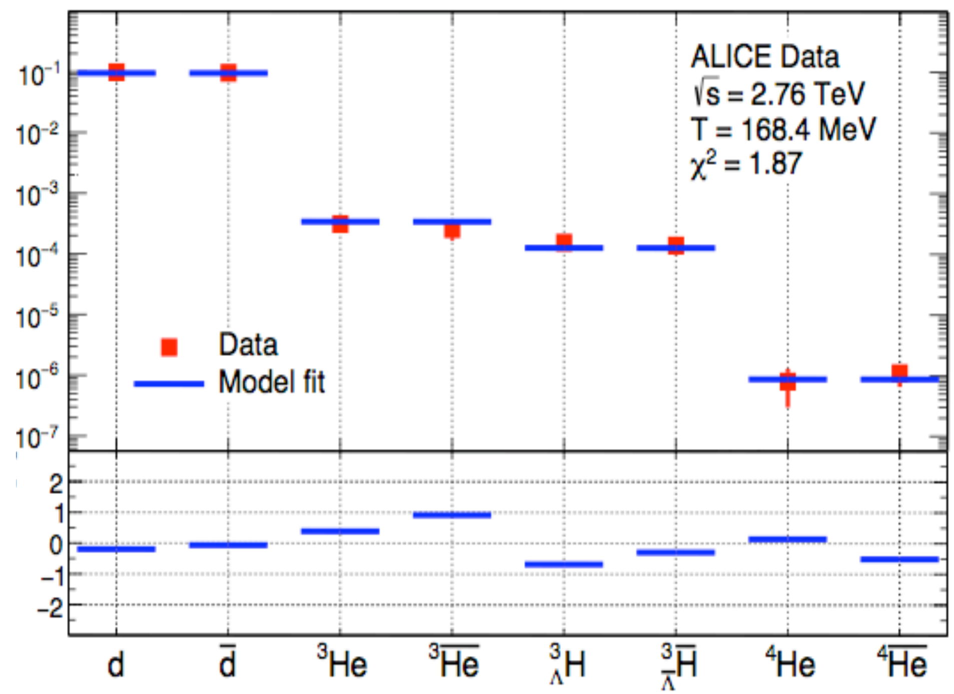
Separate CFO of Nuclei and Hadrons (New)

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

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

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

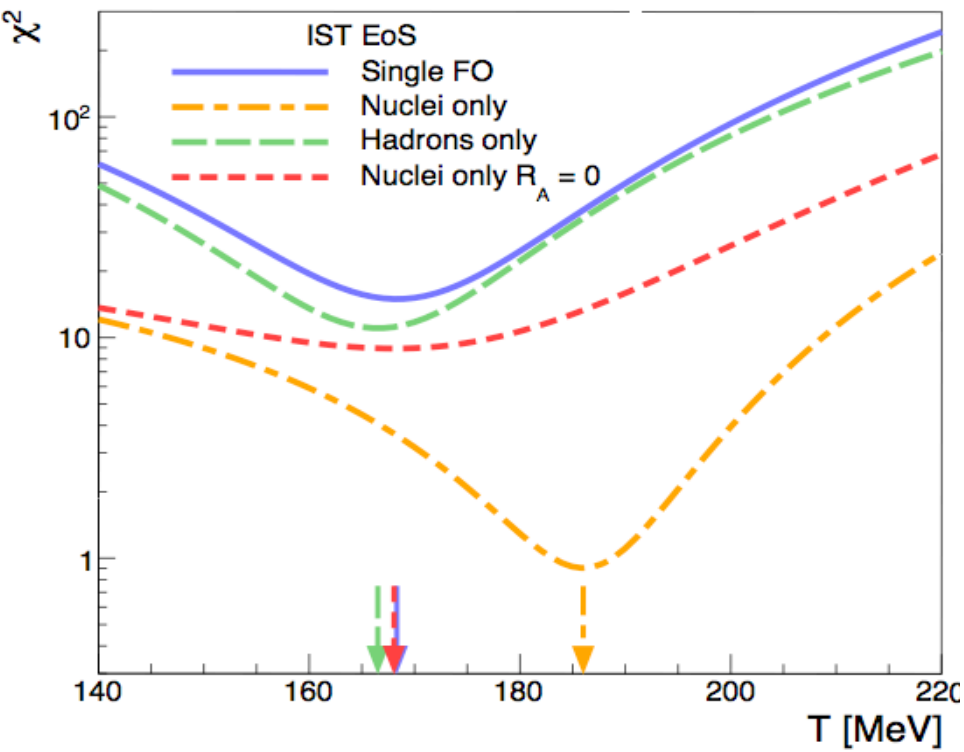


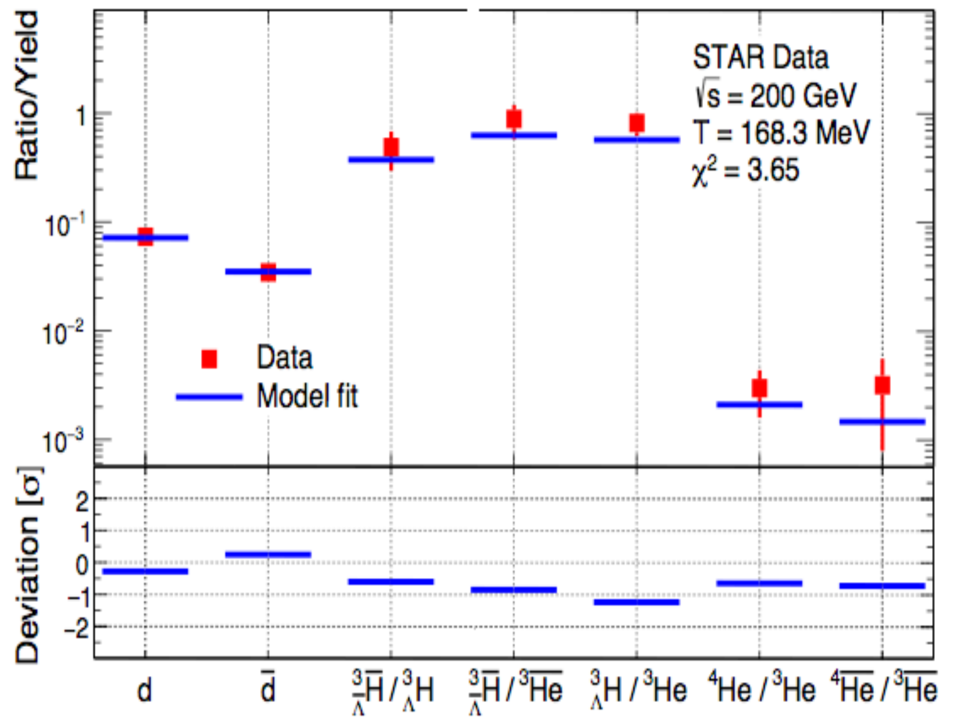


KAB et al, arXiv:2005.01555v1 [nucl-th]

STAR data √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

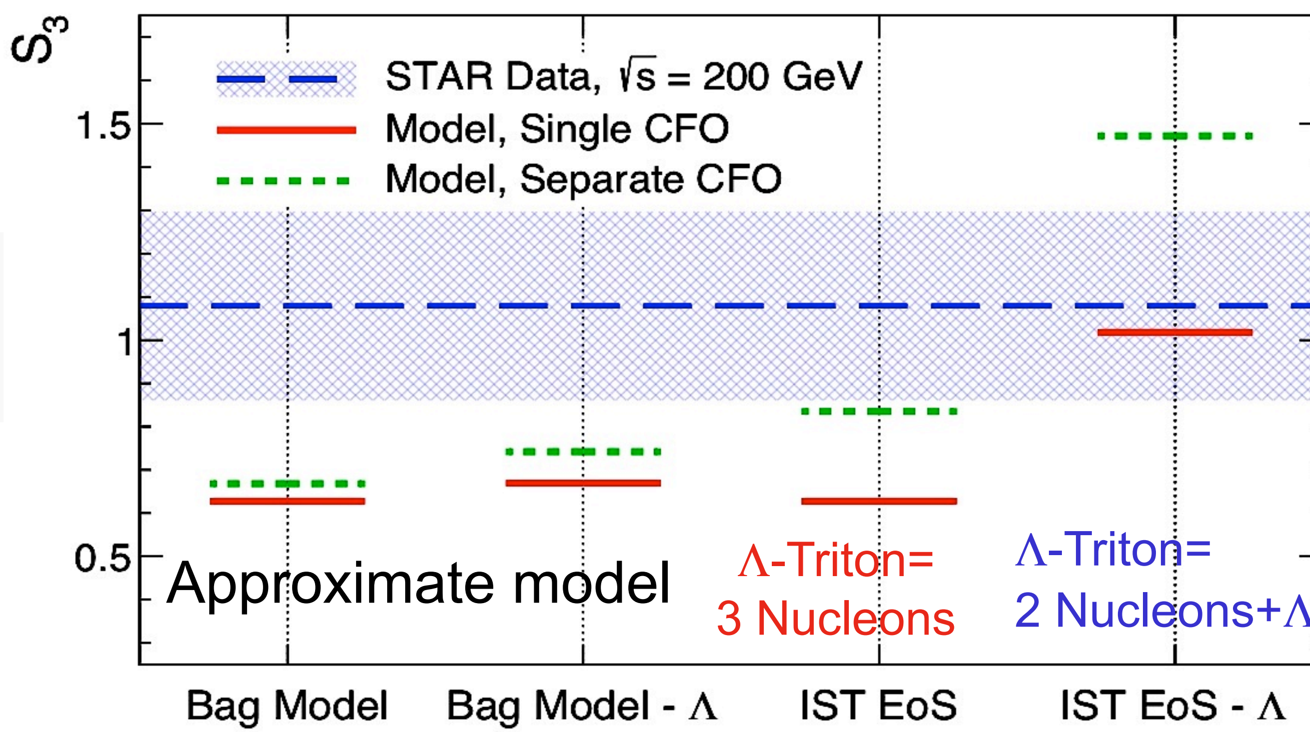
O. Vitiuk, E. Zherebtsova et al., arXiv:2007.07376 [hep-ph]

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!

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



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 hyper-nuclei 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!