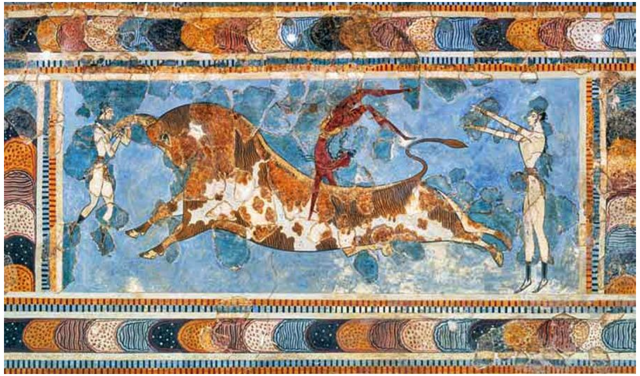
Ambiguities in the hadro-chemical freeze-out of Au+Au collisions at SIS18 energies and how to resolve them

based on: arXiv:2104.06036 [hep-ph]

Anton Motornenko

Frankfurt Institute for Advanced Studies

In collaboration with: **Jan Steinheimer, Volodymyr Vovchenko, Reinhard Stock, Horst Stöcker**



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Stiftung Polytechnische Gesellschaft Frankfurt am Main

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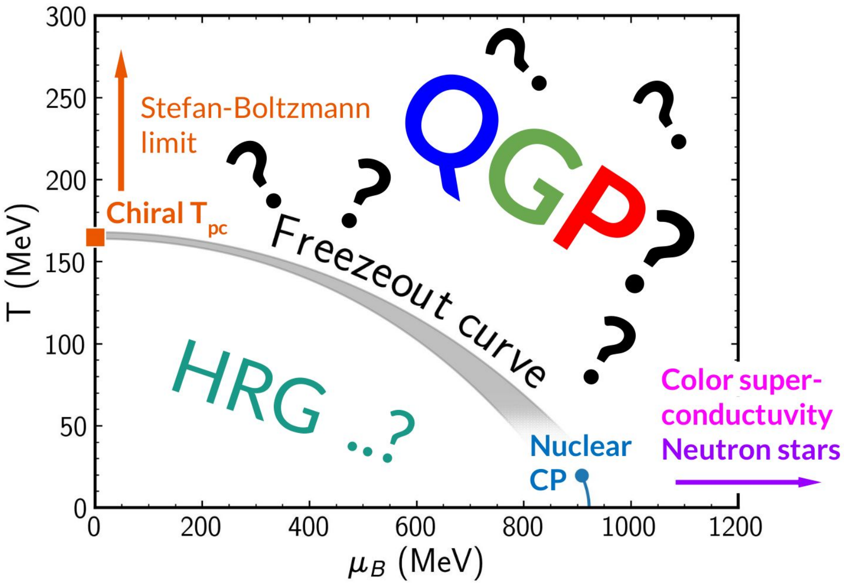
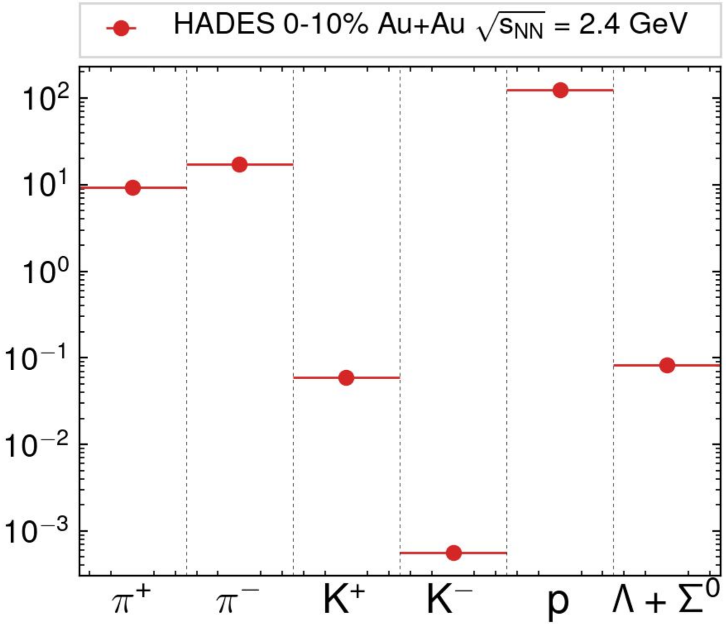
QCD phase diagram

$$\mathcal{L}_{\mathrm{QCD}} = \sum_{i,j} \bar{\psi}_i \left(i\gamma^\mu \left(\partial_\mu \delta_{ij} - \frac{i}{s} g \mathcal{A}^a_\mu \lambda_{a,ij} \right) - m_i \delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$
$$G^a_{\mu\nu} = \partial_\mu \mathcal{A}^a_\nu - \partial_\nu \mathcal{A}^a_\mu + g f^{abc} \mathcal{A}^b_\mu \mathcal{A}^c_\nu$$

How to map the well established QCD theory to its phase diagram?



Chemical freeze-out at SIS18 energies



J. Adamczewski-Musch et al. (HADES), 1703.08418
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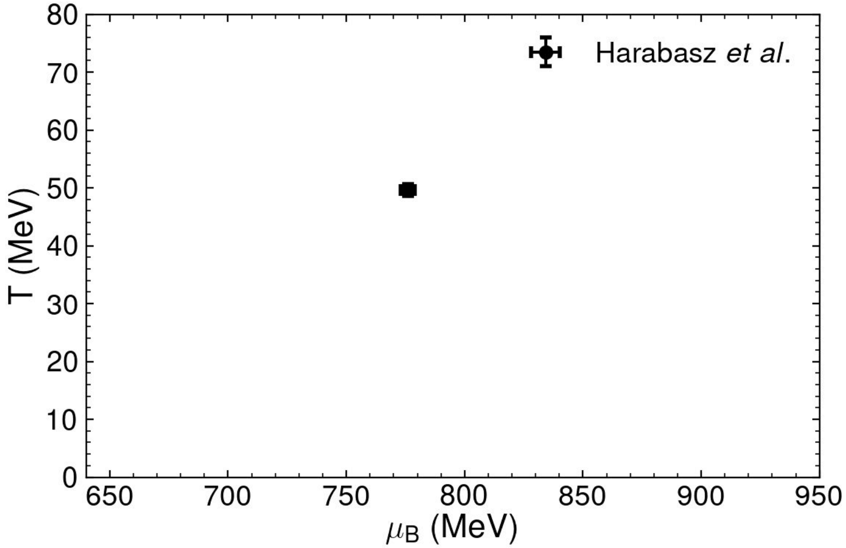

S. Harabasz et al., 2003.12992

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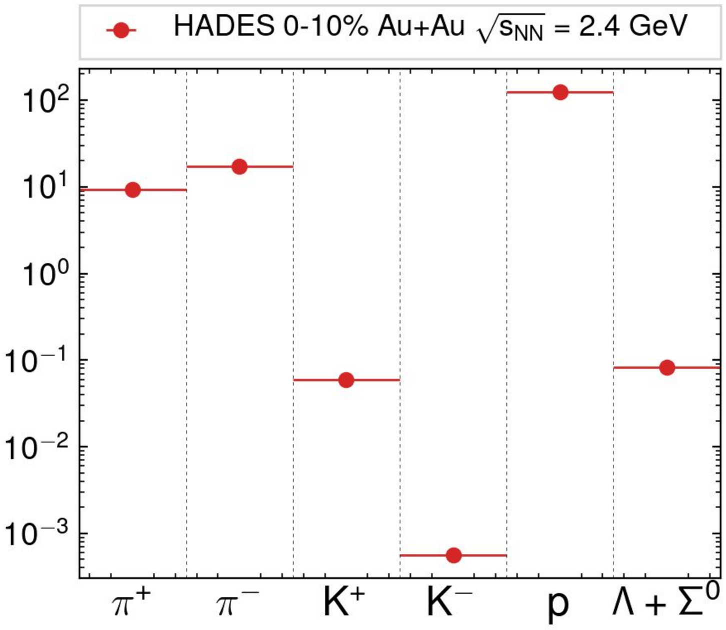

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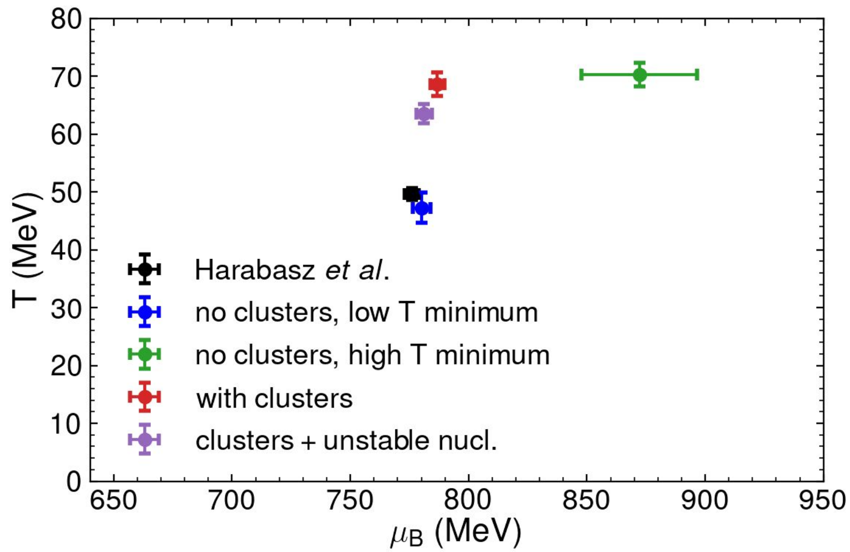

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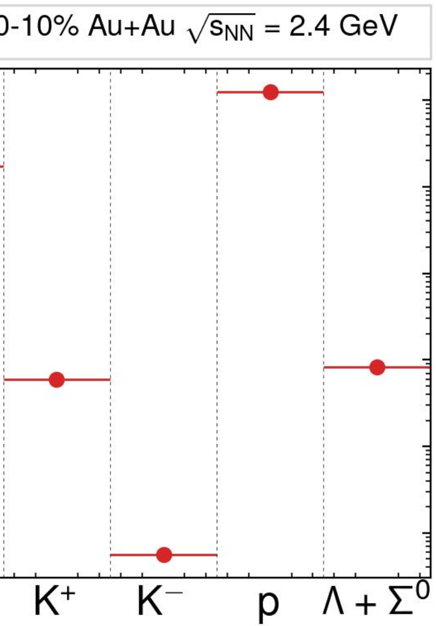

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Thermal-FIST

(*Vovchenko, Stoecker, 1901.05249*)
open source: github.com/vlvovch/Thermal-FIST

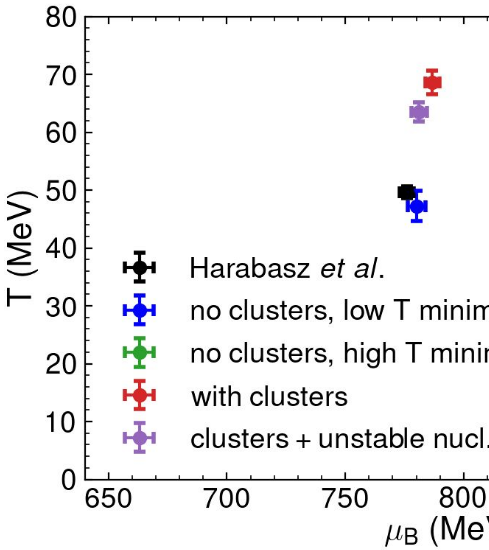
Fitting of the experimental data by **ideal non-interacting hadron resonance gas** (HRG), 4 parameters are fitted:

- baryon chemical potential μ_B
- temperature **T**
- radius **R**
- strangeness suppression factor γ_s

2 parameters are extracted from constraints:

- strangeness chemical potential μ_S from strangeness neutrality $n_S=0$
- electric chemical potential μ_Q from strangeness $n_Q/n_B=0.4$

Allows to map the experimental data to thermodynamic properties



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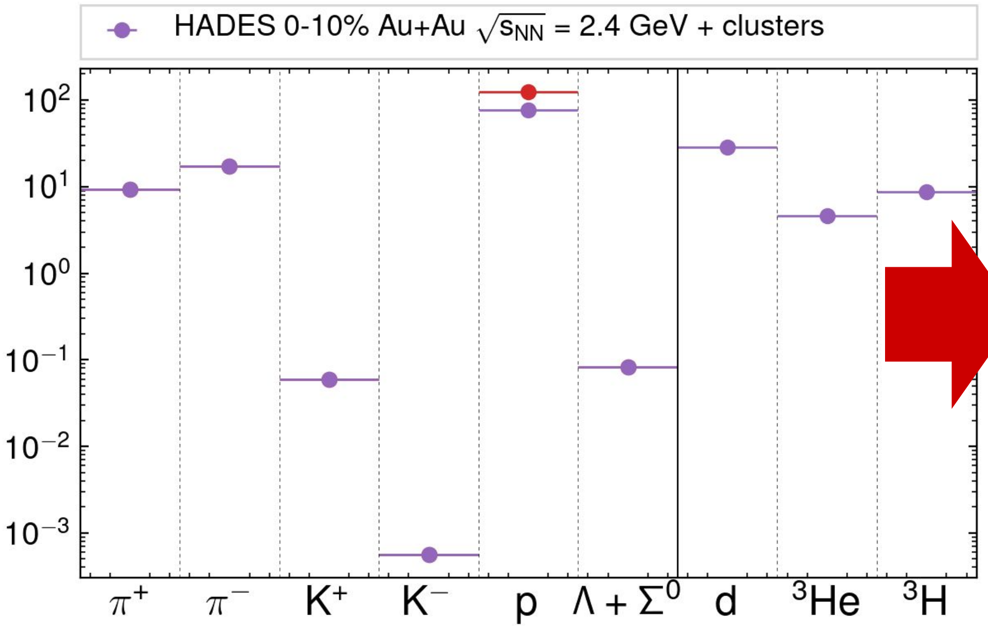

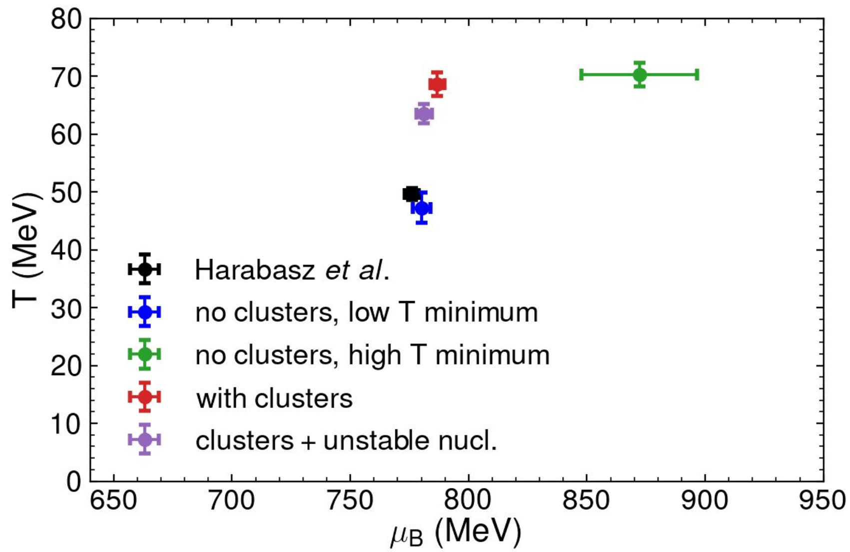

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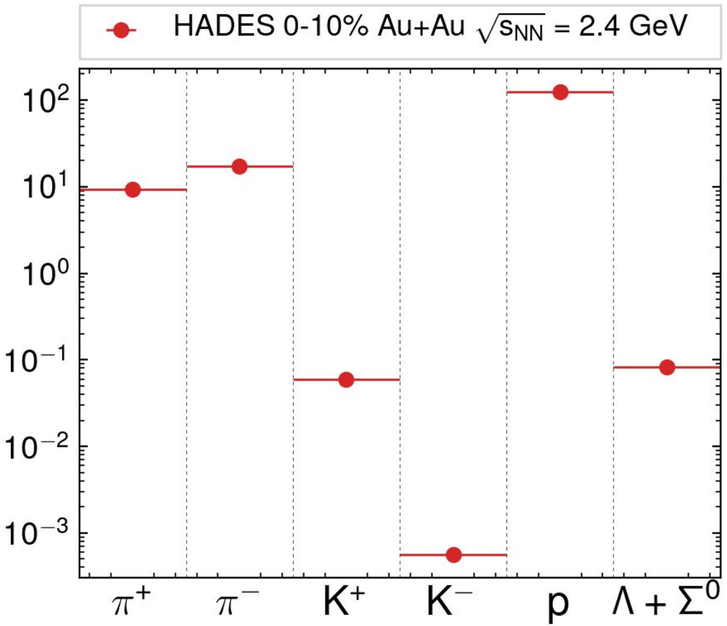
Treatment of light nuclei is important:

- either $N_p = N_{p\ unbound} + N_p(d) + N_p(^3He) + N_p(^3H)$
- either d, ^{3}He, ^{3}H are separate degrees of freedom

Ambiguities in the freeze-out: double minima



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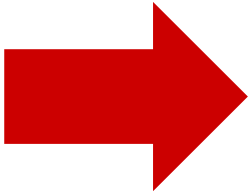

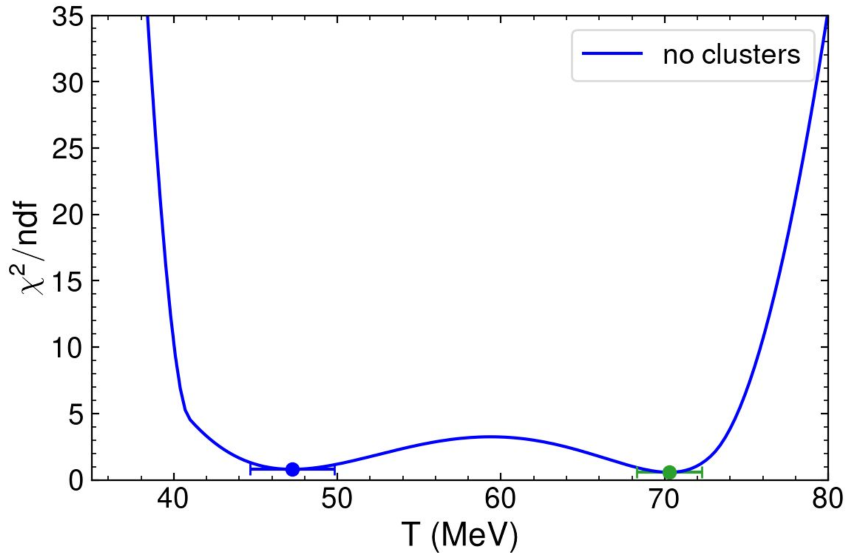

Thermal fit to the hadron yields has two degenerate solutions.

- **Which solution to choose?**
- **Higher T solution was not found in *Harabasz et al.***
- **No freeze-out at all?**

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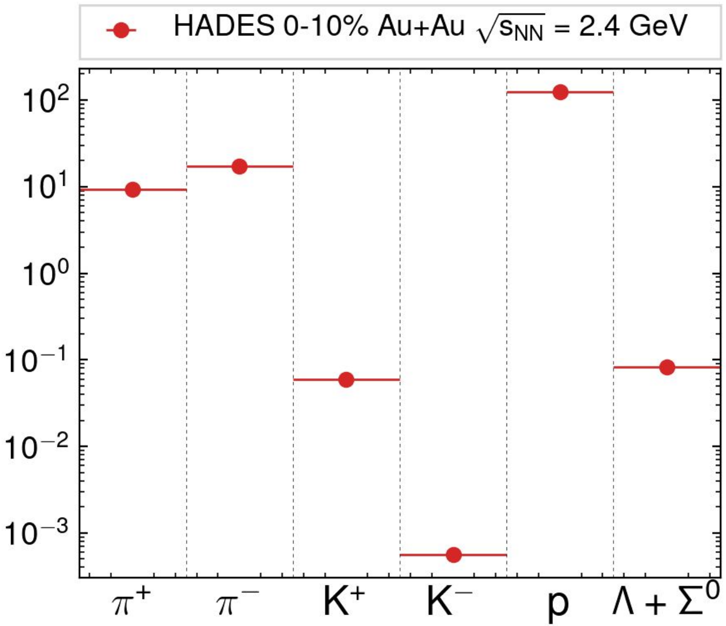

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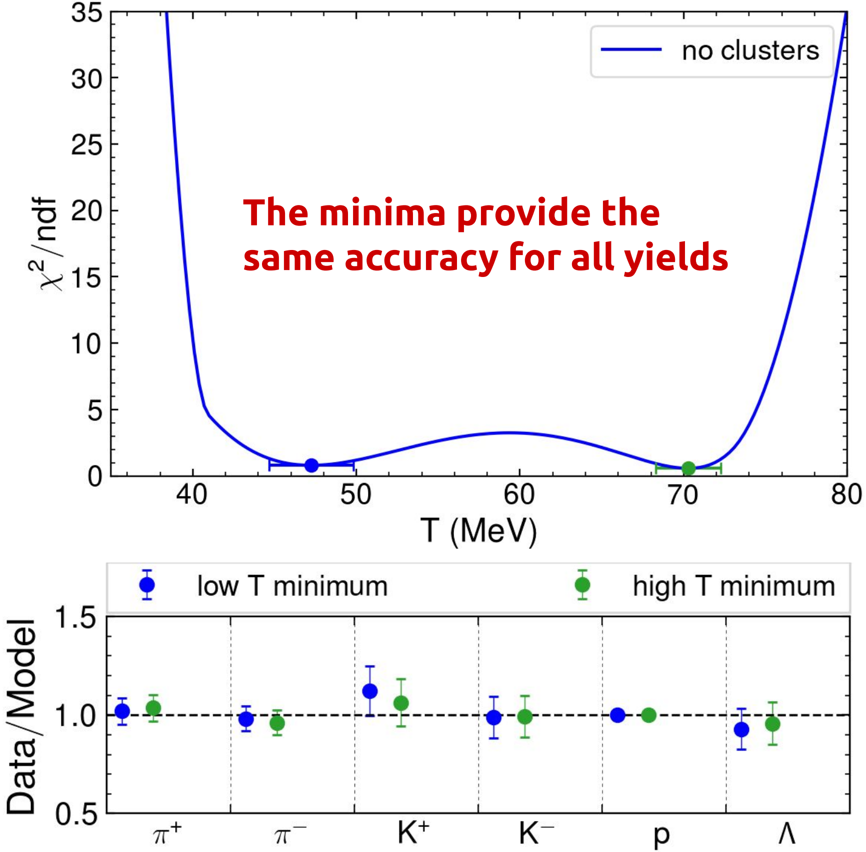
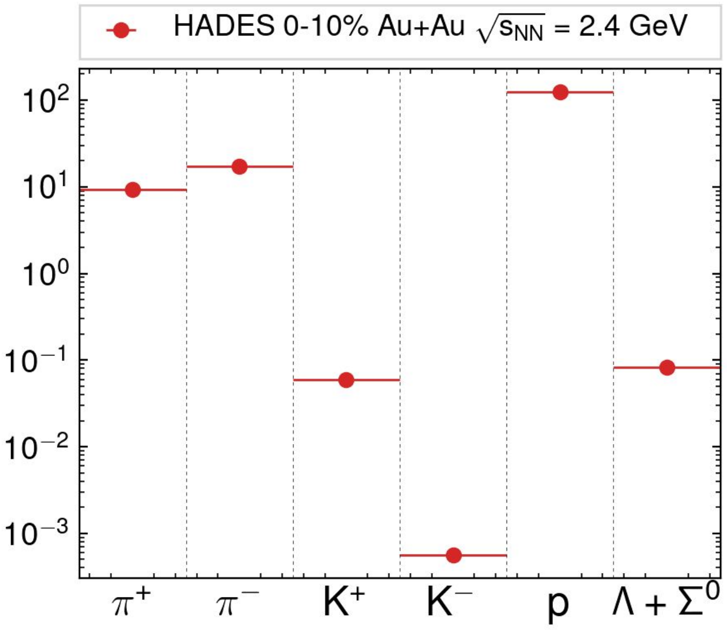


The minima provide the same accuracy for all yields

Ambiguities in the freeze-out: double minima



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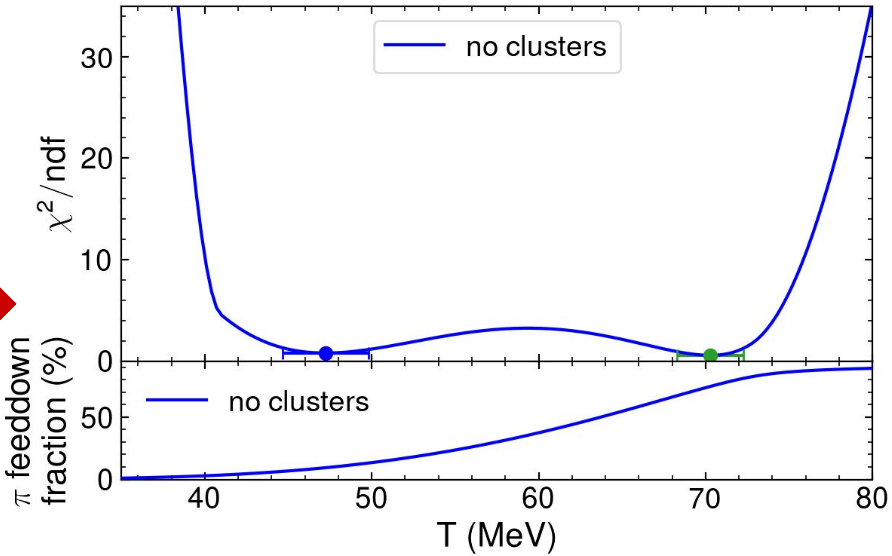
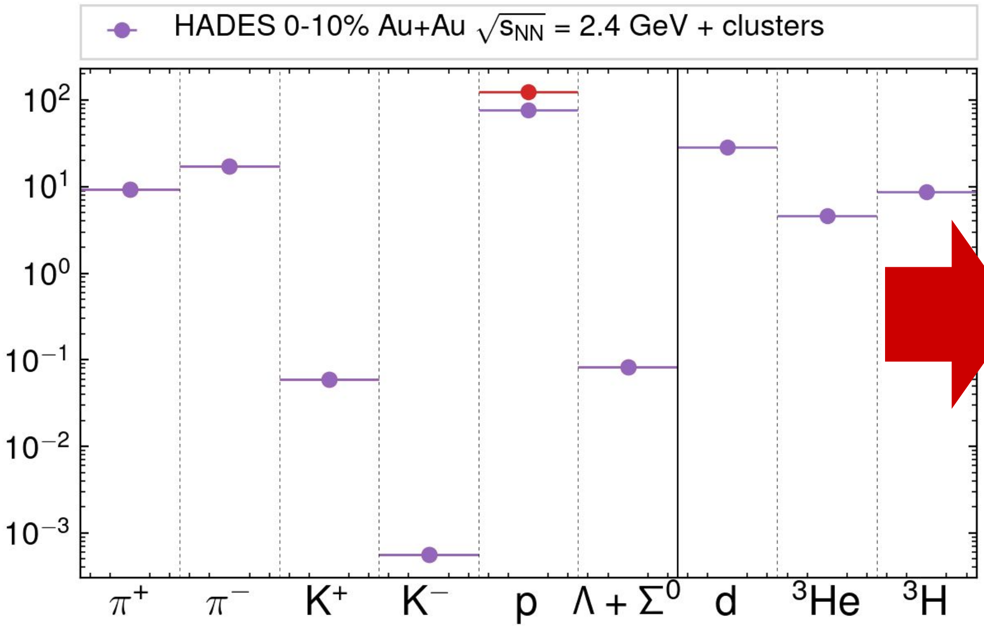
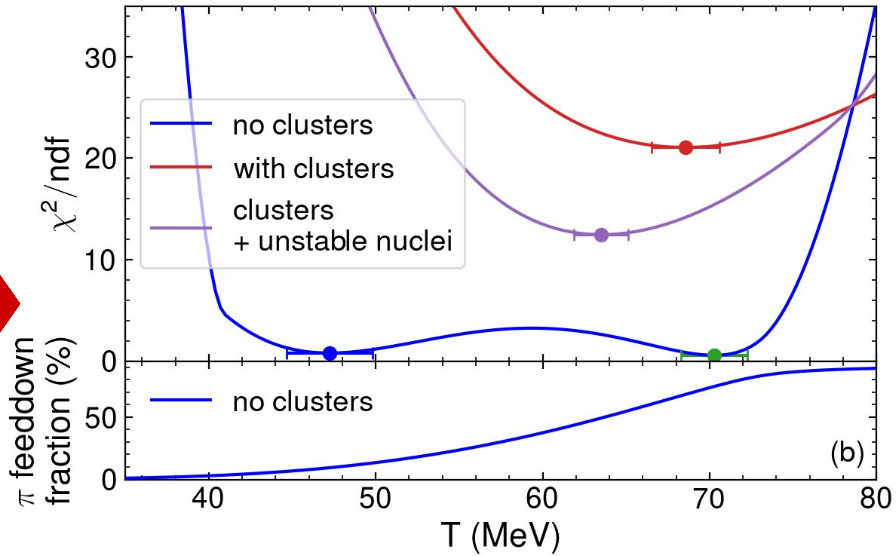


Two minima have completely different resonance content.
At the higher temperature more than 70% of pions come from the resonance decays.

Ambiguities in the freeze-out: light nuclei





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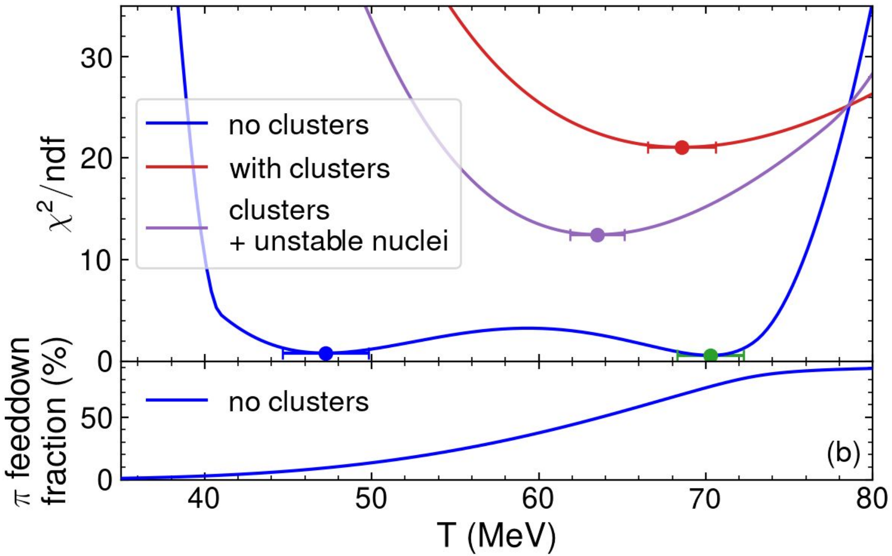
Fit with light nuclei as separate degrees of freedom:

- Single minima
- Data is poorly described, χ^2/ndf > 10

Ambiguities in the freeze-out: all scenarios

Three scenarios:

- **no clusters** – light nuclei are formed after the chemical freeze-out, thus are omitted from the thermal model particle list. Protons that later-on bind into the light nuclei are counted as 'free'
- **clusters included** – light nuclei are formed at the chemical freeze-out. Only stable light nuclei are included in the thermal model particle list.
- **clusters and decays of unstable nuclei** – the model includes the feeddown from the decays of *unstable* A = 4, and A = 5 nuclei to the final yields of protons, deuterons, tritons, ^{3}He, and ^{4}He at the chemical freeze-out (*Vovchenko et al., 2004.04411*).



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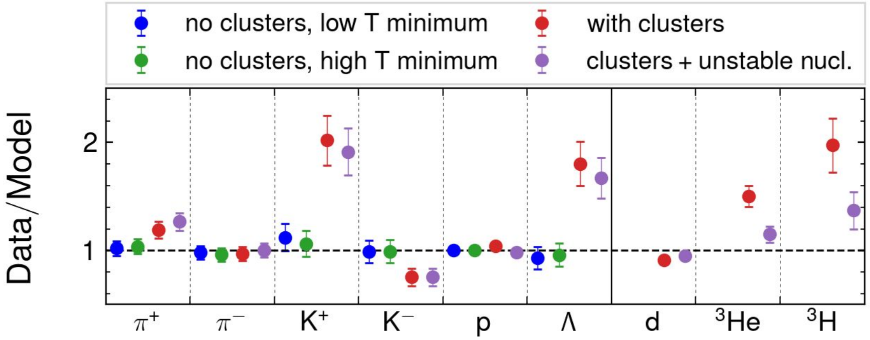
- Good description, **arbitrary T possible**
  Which T to choose?
- Poor description, single minimum
  Another mechanism for light nuclei formation should be considered.
- Improved description, single minimum
  Perhaps this scenario can be improved?..



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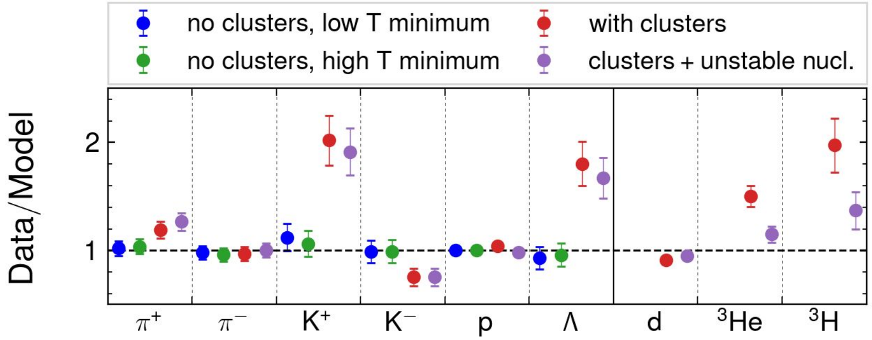
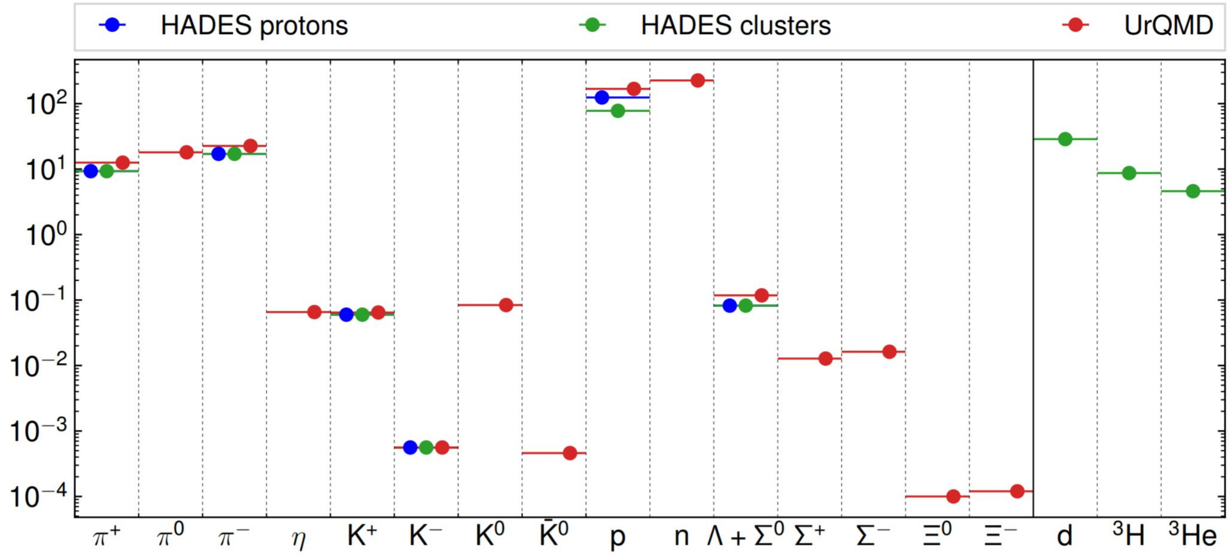


Resolving ambiguities: freeze-out in UrQMD



UrQMD predictions for particle yields in Au+Au@$\sqrt{s_{NN}}$ = 2.4 GeV can be used as input to thermal model.

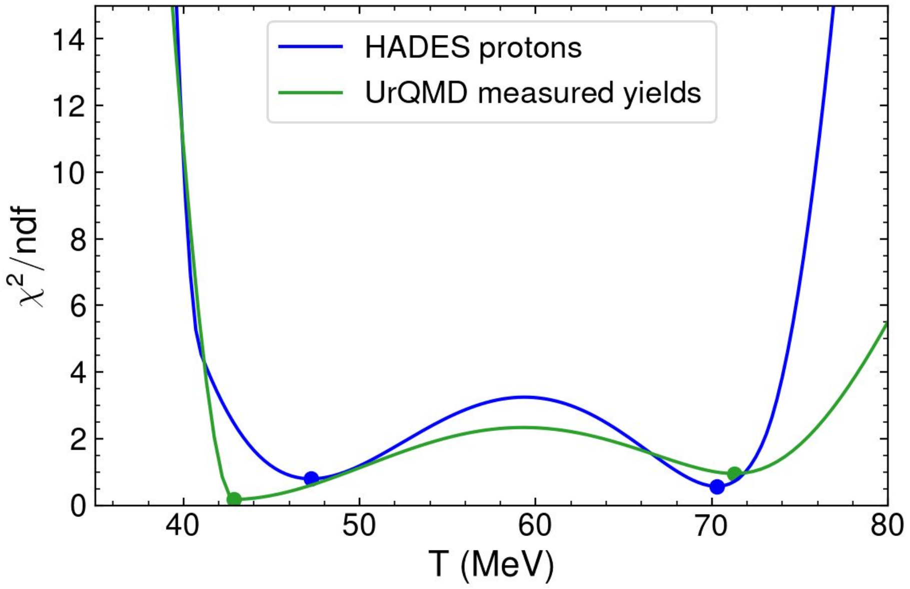
More stable hadrons in the fit — possibility for a unique solution.

UrQMD 3.4 extended with up-to-date resonance branching ratios works well in the HADES energy regime. Inclusion of density-dependent nuclear potentials is essential.

G. Graef et al., 1409.7954
J. Steinheimer et al., 1503.07305
P. Hillmann et al., 1802.01951
F. Seck et al.,2010.04614

Resolving ambiguities: UrQMD χ^2 profiles

UrQMD prediction for particle yields **reproduces the double-minimum structure** for the fit to the measured ($\pi^{+,-}$, K^{+-}, p, Λ) yields.



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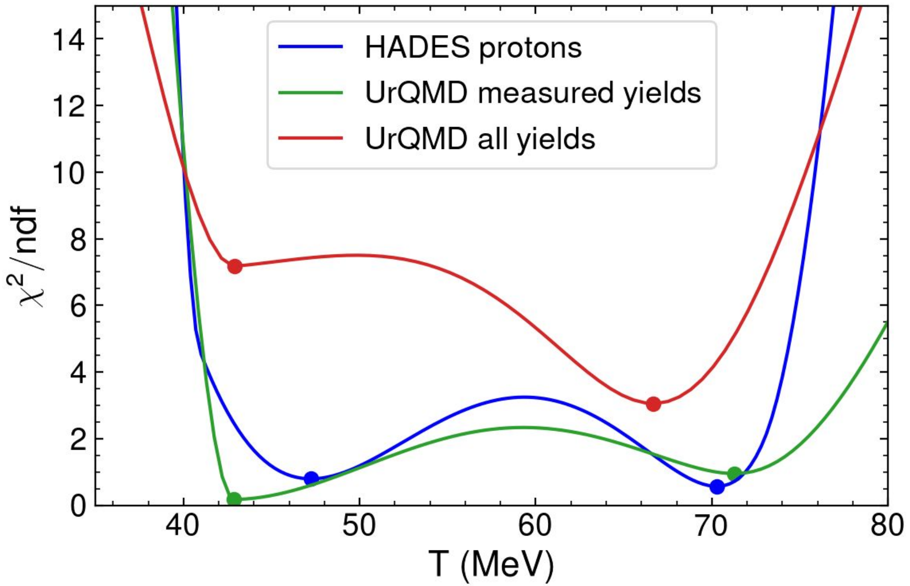
The fit to all stable hadron yields **favors higher T minimum**.



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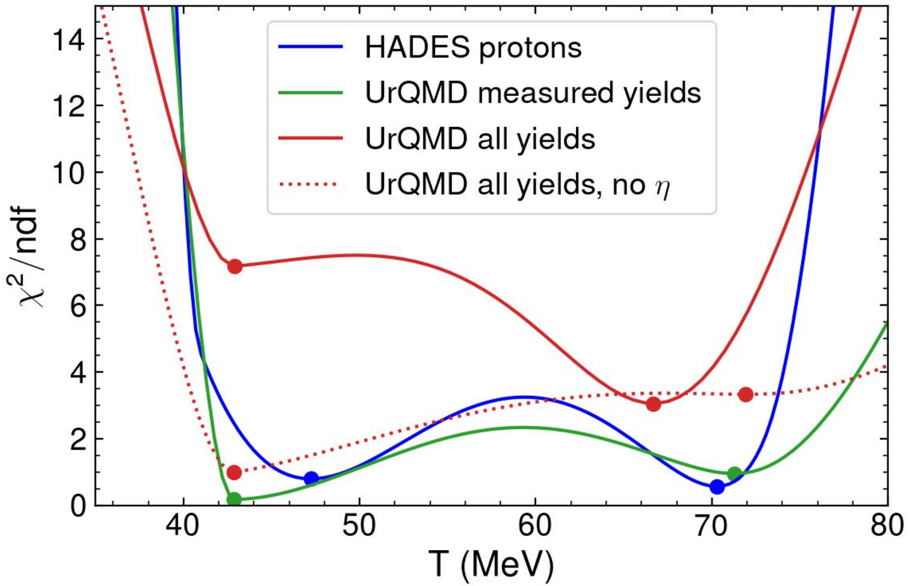
However, it's very sensitive to the yield of the scalar η meson which is very temperature-sensitive.



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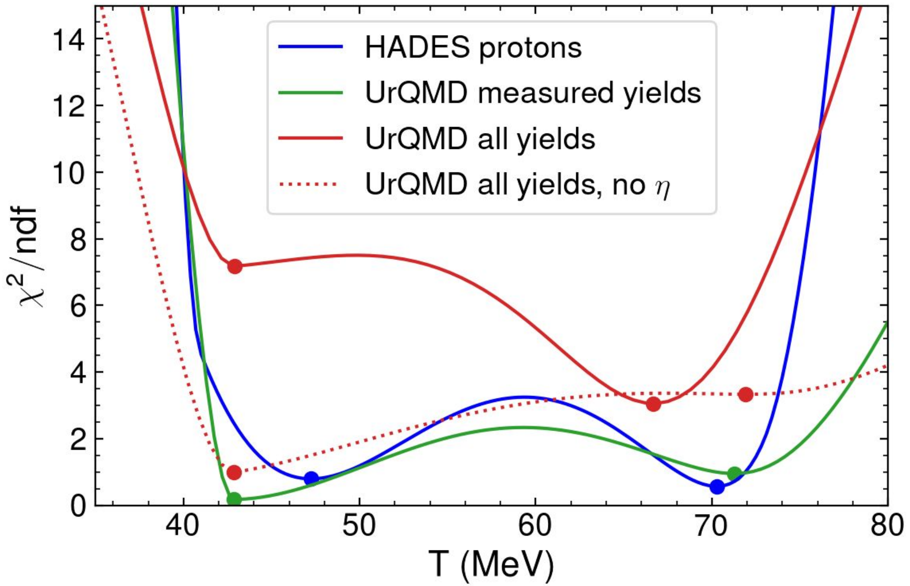


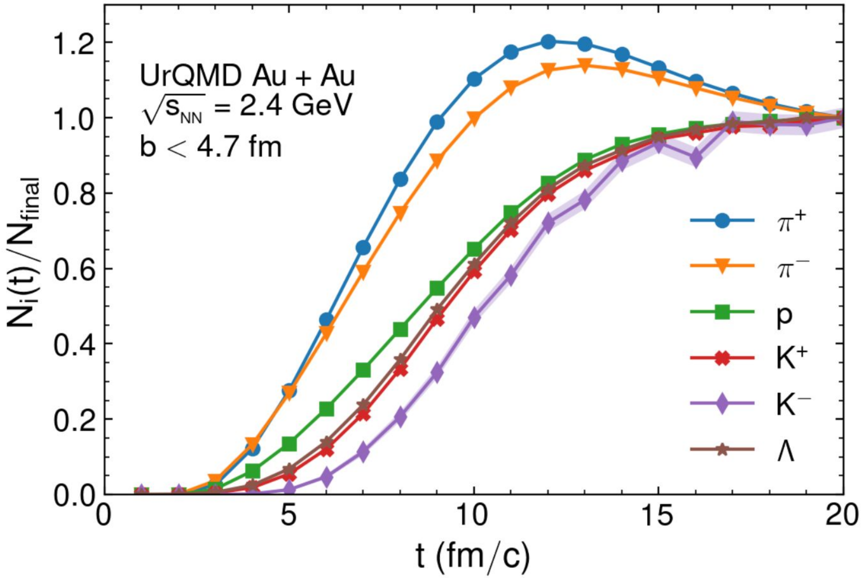
If the best fit depends strongly on the choice of included hadron multiplicities, perhaps, there is no universal chemical freeze-out?..

Resolving ambiguities: fit evolution

How do the minima reveal themself during the fireball evolution? Perhaps they appear one after another?

The evolution can be tracked by **fitting time-dependent particle yields** extracted from UrQMD (*Steinheimer et al., 1603.02051*):

- the UrQMD evolution is stopped at time ***t***
- all unstable hadrons are forced to decay
- the calculated hadron yields are related to time ***t***



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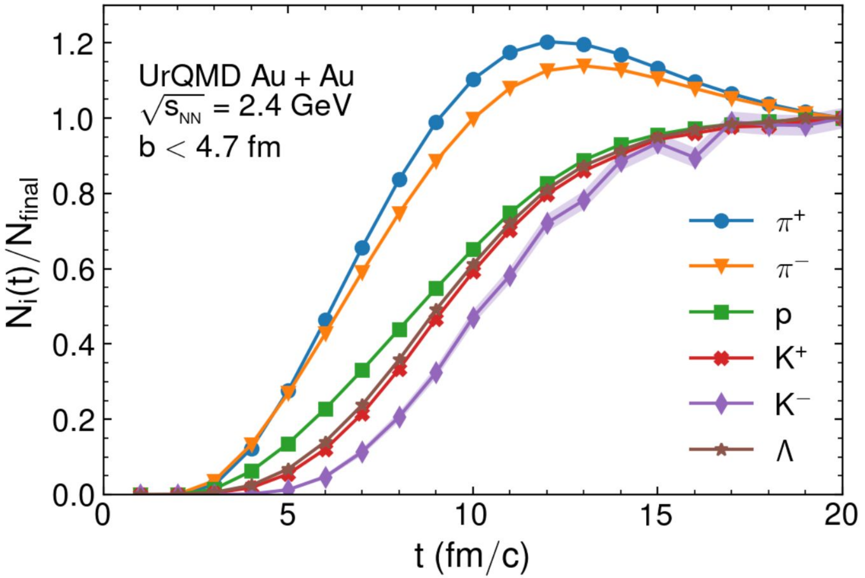
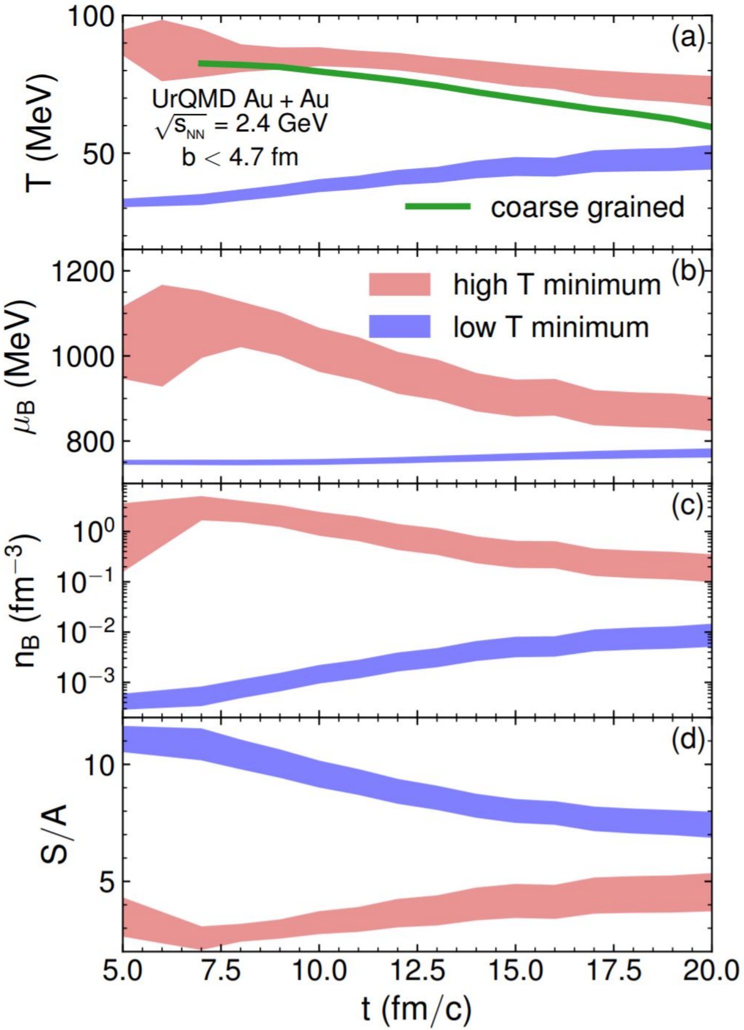




Fit to time-dependent particle yields allows to extract thermodynamic properties at each time ***t***.

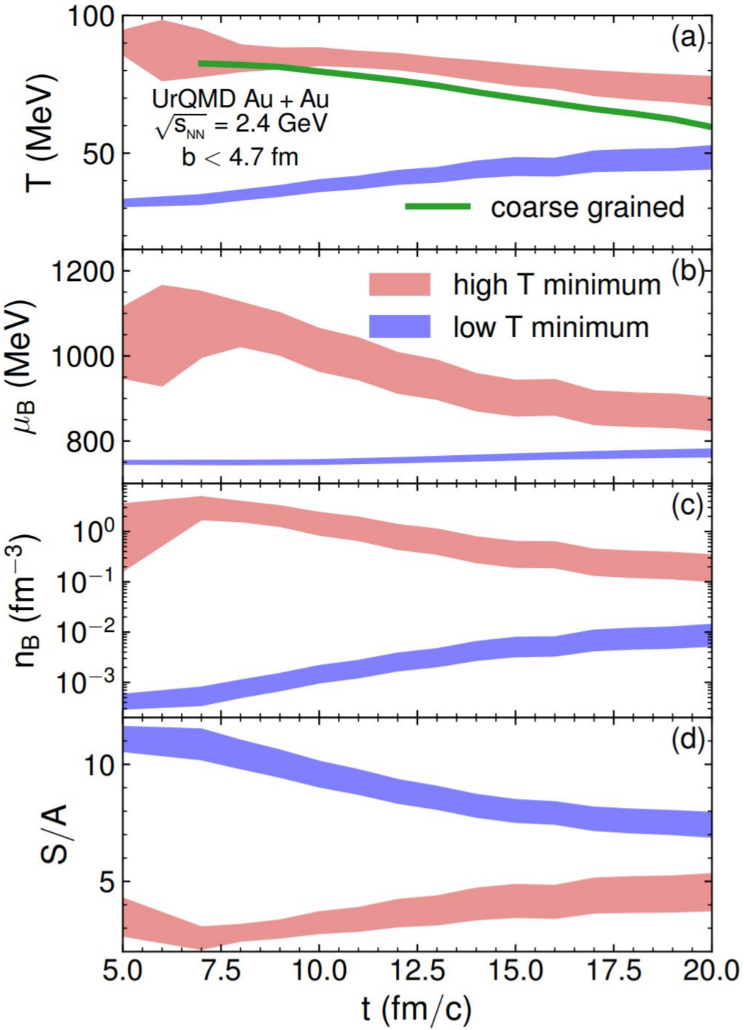
Anton Motornenko, *2104.06036*

Resolving ambiguities: fit evolution

The double minimum structure in the fit is found throughout the whole evolution.

The high temperature minimum behaves as "classical" picture of the fireball evolution:
temperature and density (chemical potential) decrease with time as a result of the fireball cooling during the expansion.

The low temperature minimum seems to violate the second law of thermodynamics:
total entropy per baryon strongly decreases with time ΔS/A(t) < 0, temperature increases, density decreases



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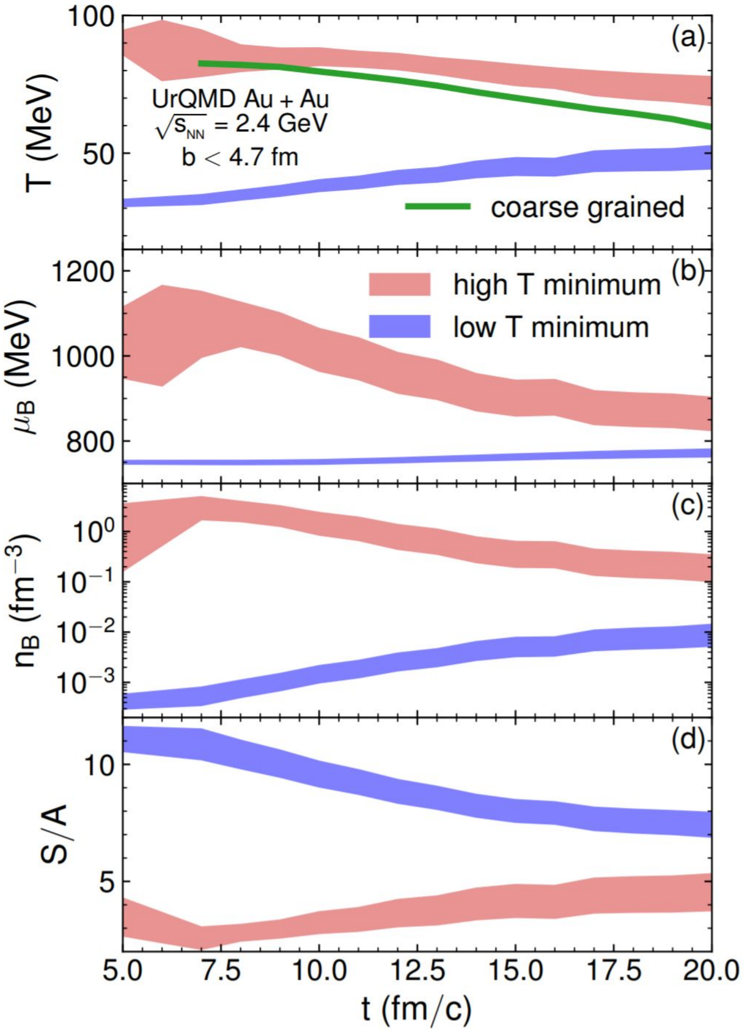
The low temperature solution behaves unphysically!



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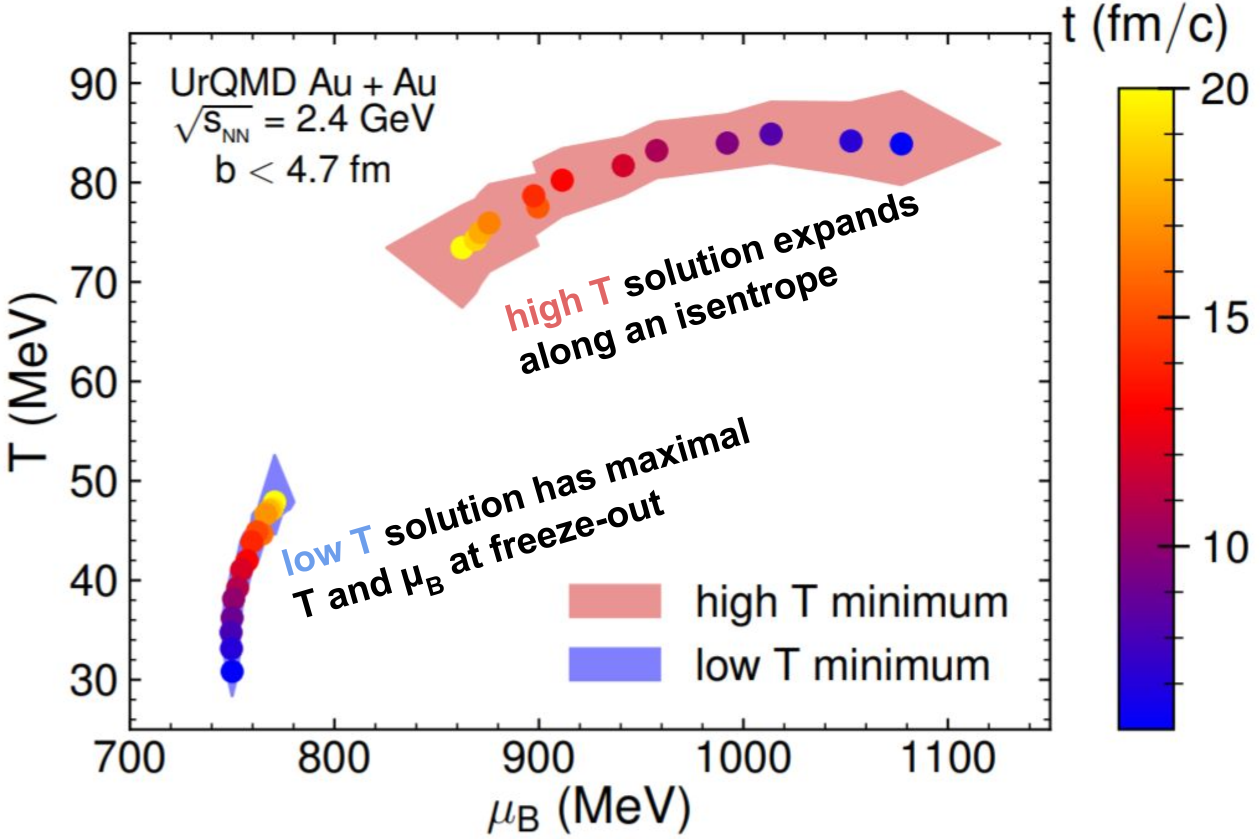
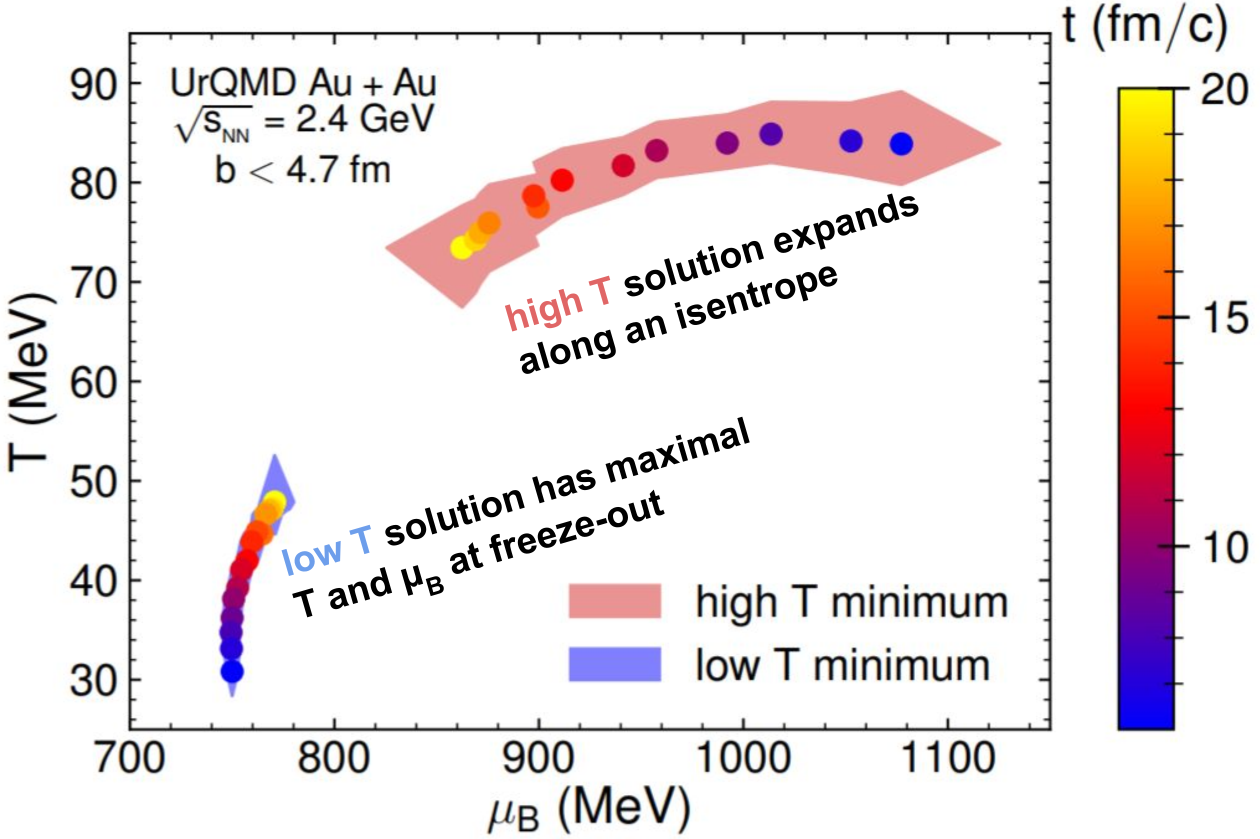


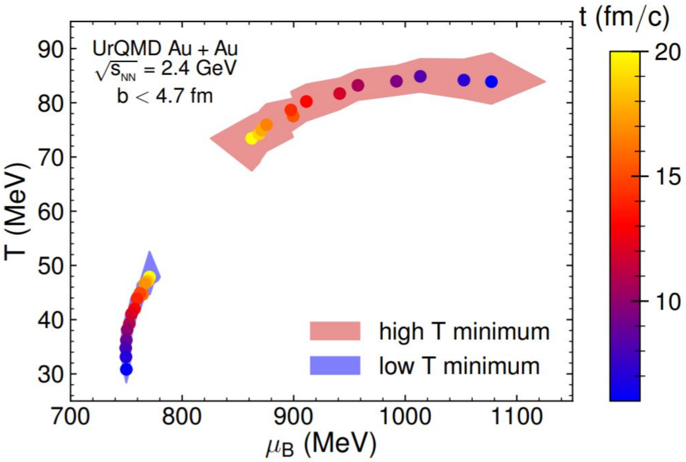
Resolving ambiguities: fit evolution

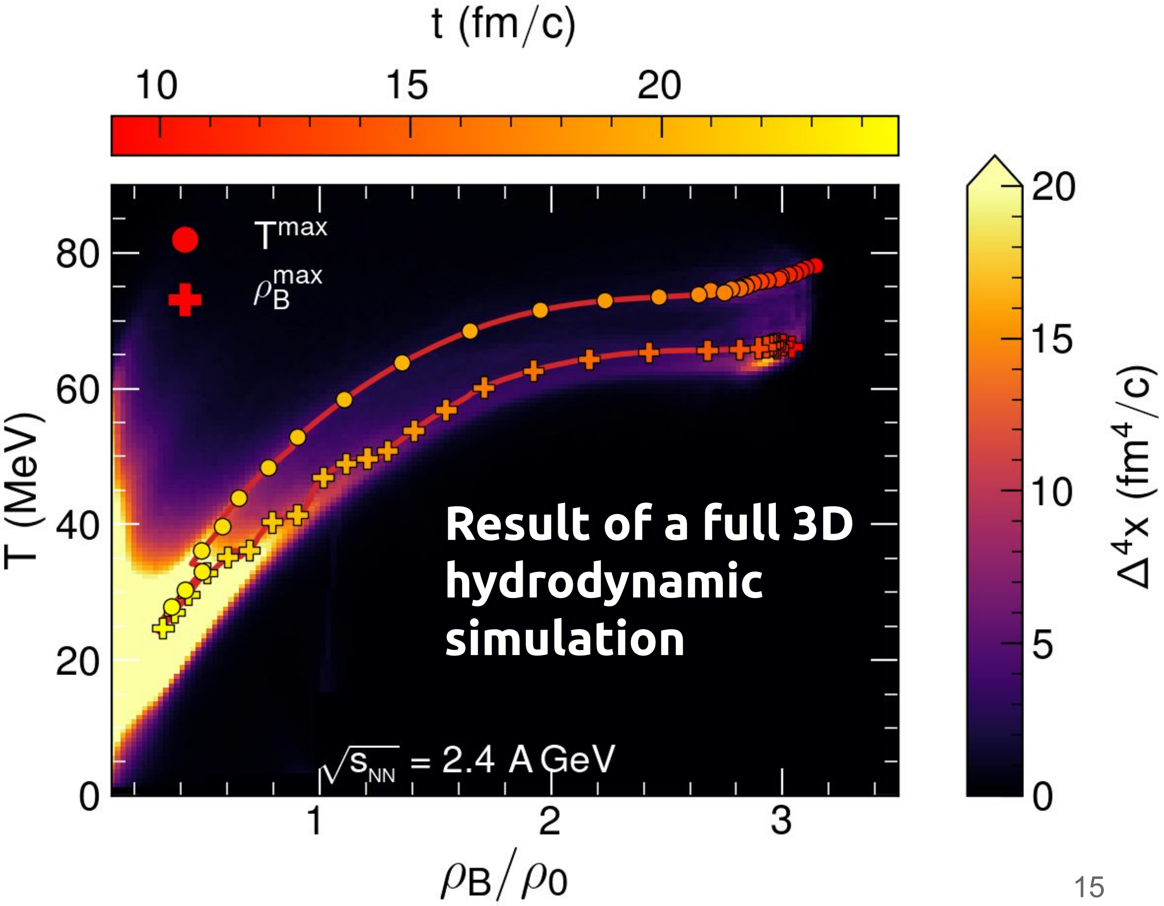
Only the high T solution can be considered physical.



Resolving ambiguities: fit evolution

One shouldn't forget:
Heavy ion collision is a very complex system where thermal model description is a very rude approximation.
More involving models are required.





Summary

- Thermal model **can not uniquely describe** freeze-out at SIS18 energies:
  - **two degenerate x^2 minima are present**
- Description of **light nuclei** at the freeze-out is unsatisfactory
  - … possible **room for improvement**
- Analysis of **UrQMD** data yields the **same degenerate x^2 minima**
- Additional **not-yet-measured hadrons do not allow to discern** the minima
  - **unstable hadronic species** may be helpful, but technical (*Motornenko, 1905.00866*)
- A detailed study of the time evolution of the particle yields suggests that only **the high T solution behaves physically**, **low T solution should be disregarded**

Heavy ion collision is a complex dynamical system, simple approach like thermal model is not capable for all the details

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Thank you for the attention!