The chemical freeze-out in a dynamical hadronic transport simulation

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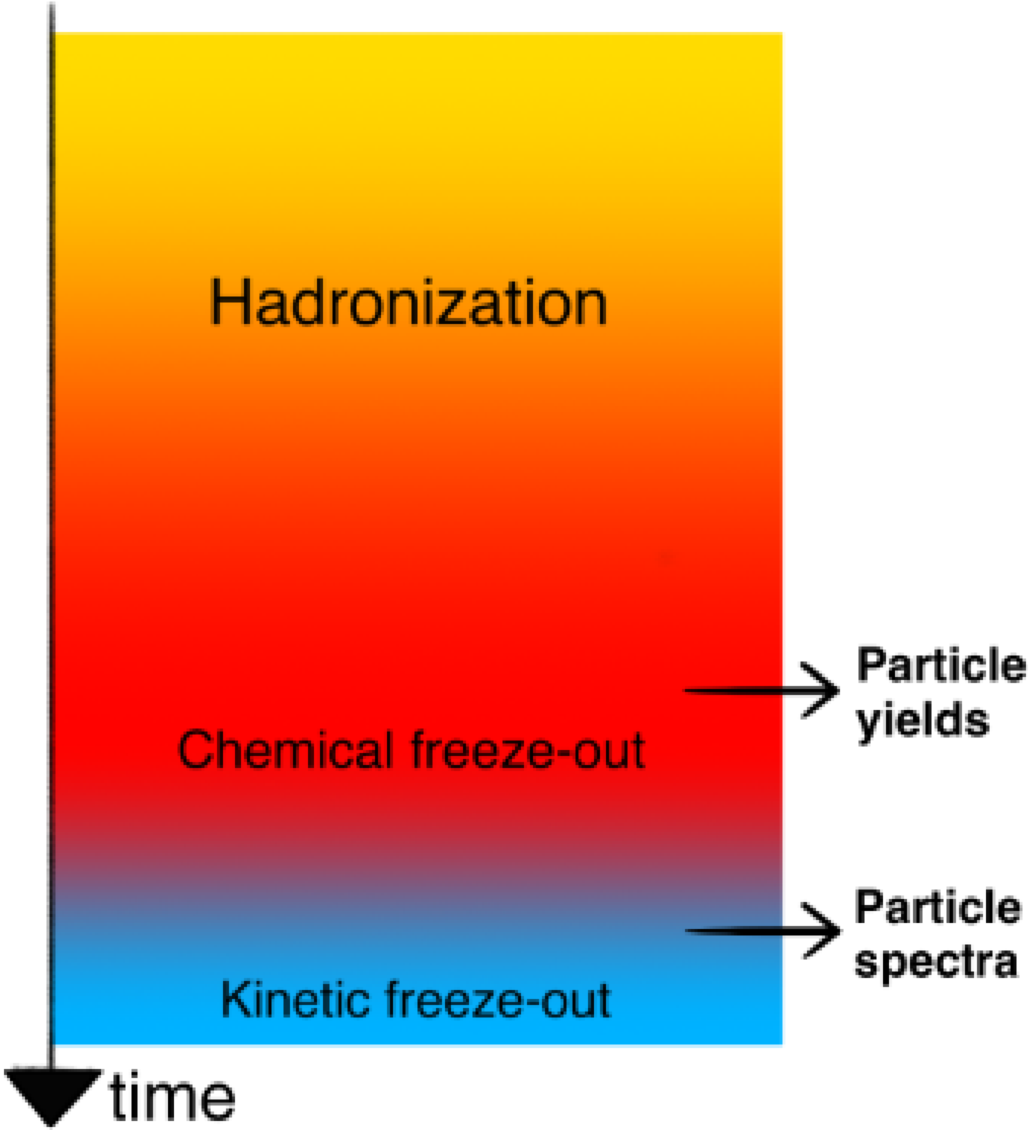
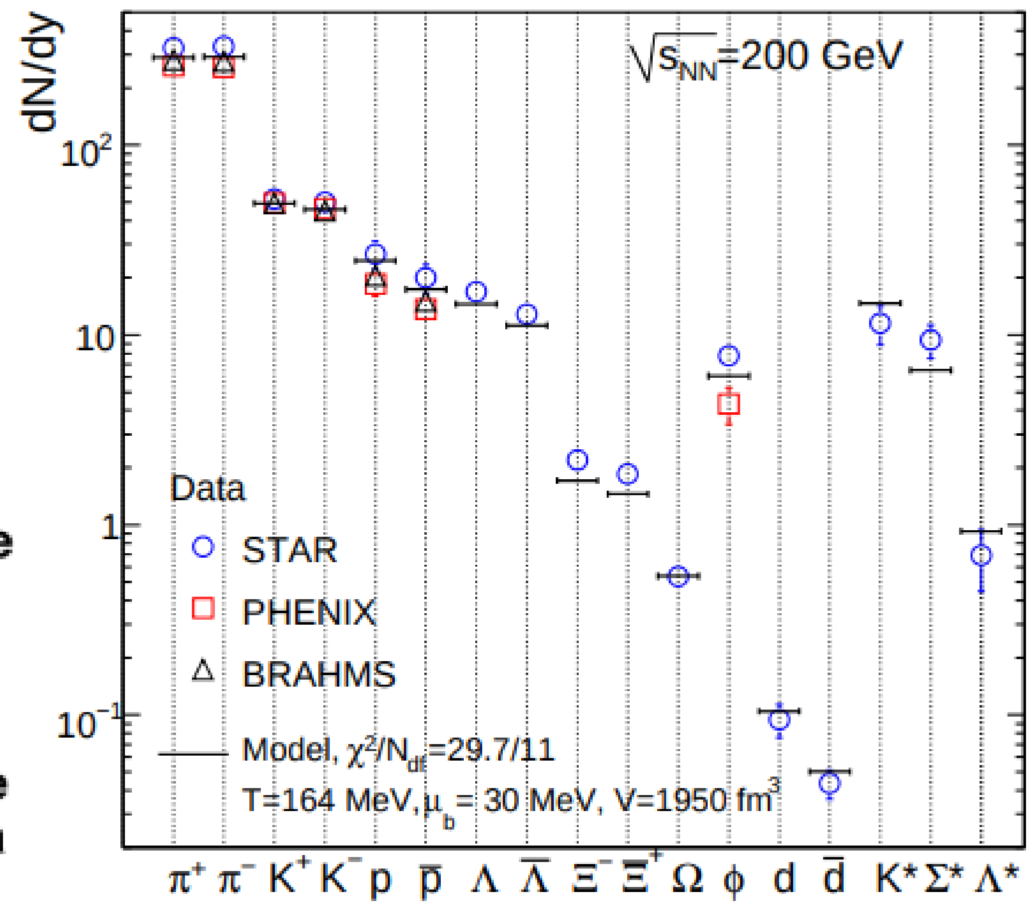
HIPSTARS - Workshop on Heavy Ion Physics and Compact Stars 2020
Contact: treichert@itp.uni-frankfurt.de, Eur.Phys.J.A 56 (2020) 10, 267 and arXiv:2011.04546

The chemical freeze-out





Andronic, Braun-Munzinger & Stachel. Phys. Lett. B 673, 142-145 (2009)

The chemical freeze-out

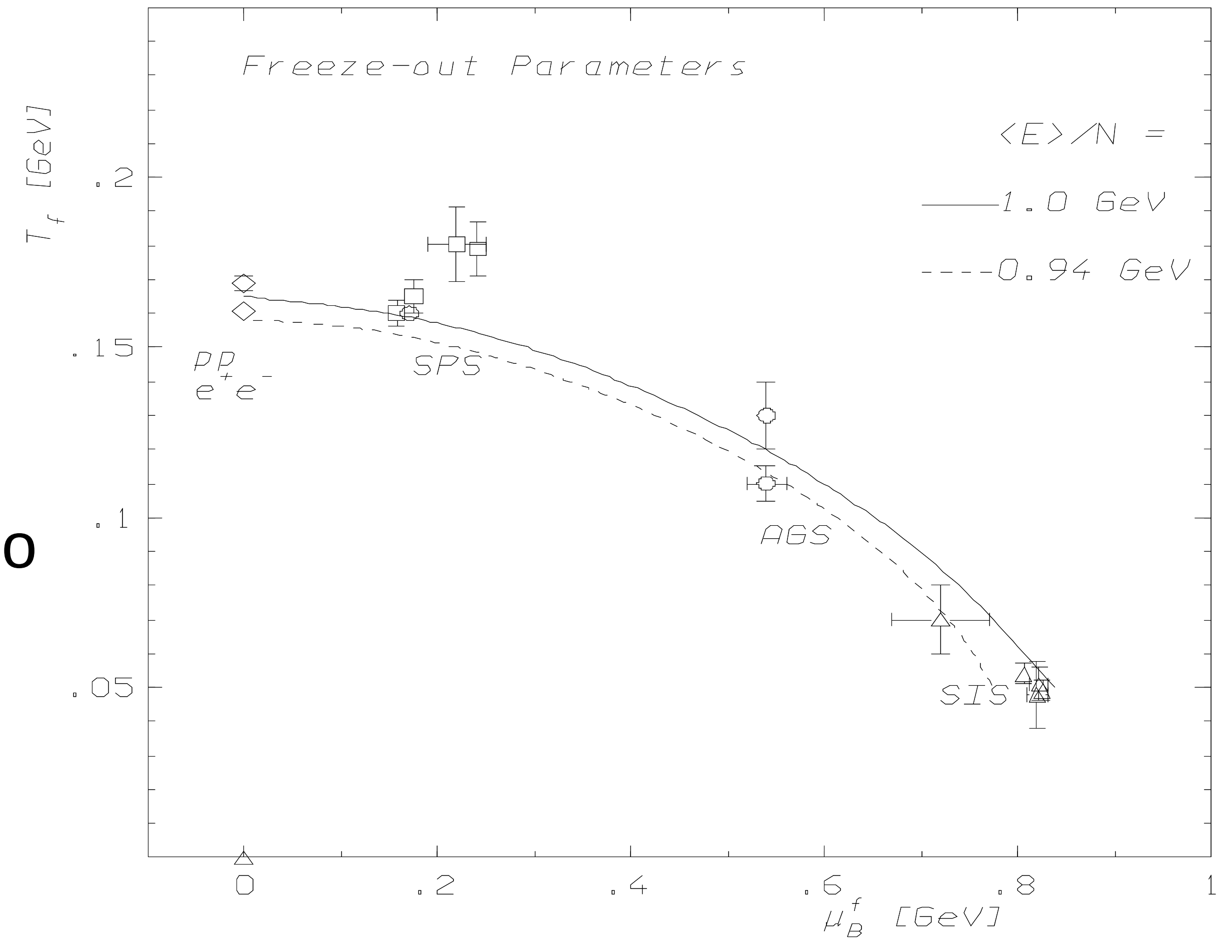
- Cleymans & Redlich: chemical freeze-out

  ↔

  1 GeV per particle

- Valid from GSI to LHC

- Valid from pp to AA, also in e^-e^+



Cleymans & Redlich. Phys. Rev. Lett. 81, 5284-5286 (1998)

The chemical freeze-out

- Interpretation?
- In a non-relativistic system:

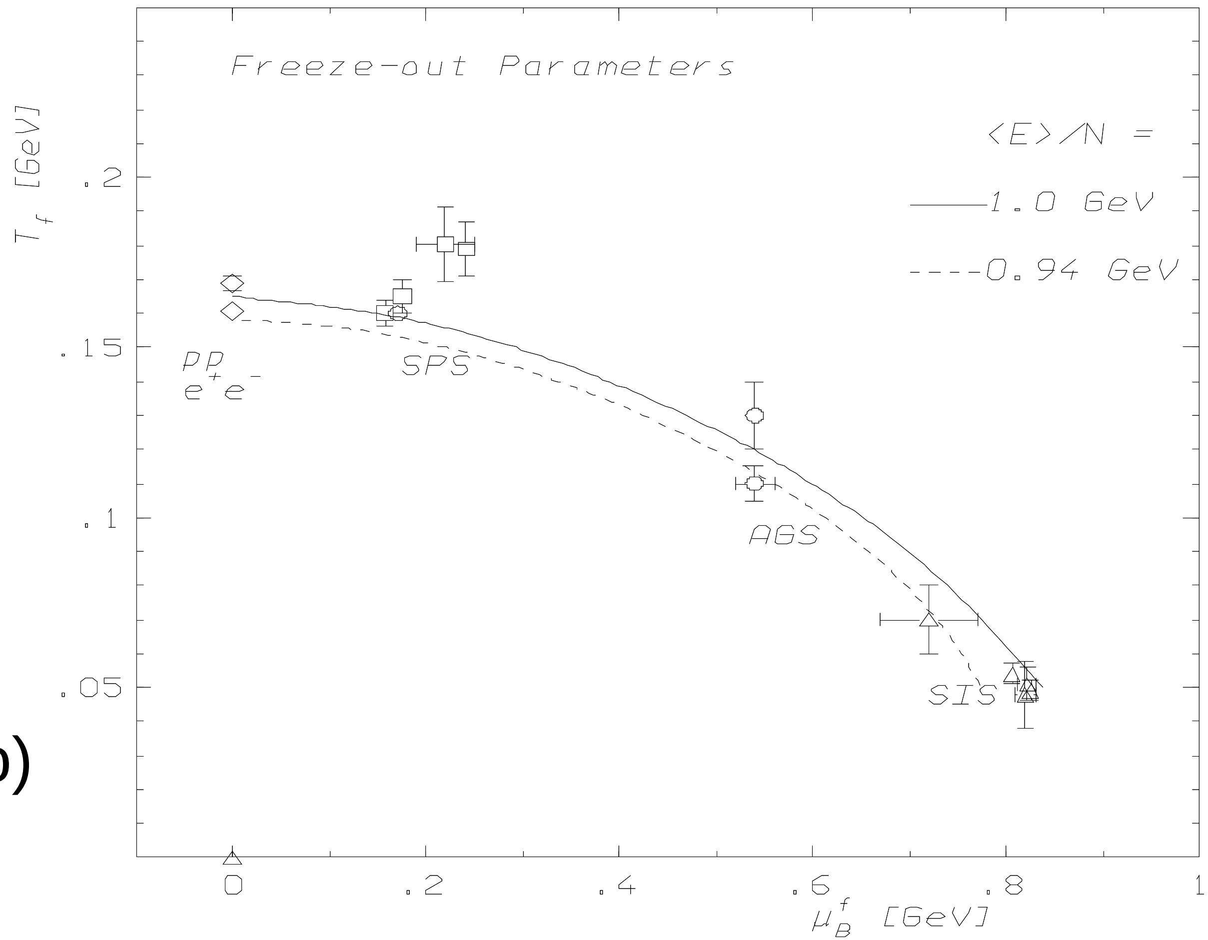
$$\langle E \rangle / \langle N \rangle \approx \langle m_{thermal} \rangle + \frac{3}{2} T$$

- SIS: nucleons at 50 MeV

$$\langle m_N \rangle + \frac{3}{2} \cdot 50\, MeV \approx 1\, GeV$$

- SPS: Pions (bound in Rho) at 150 MeV

$$\langle m_\rho \rangle + \frac{3}{2} \cdot 150\, MeV \approx 1\, GeV$$



Cleymans & Redlich. Phys. Rev. Lett. 81, 5284-5286 (1998)

Other criteria?

- Yes!

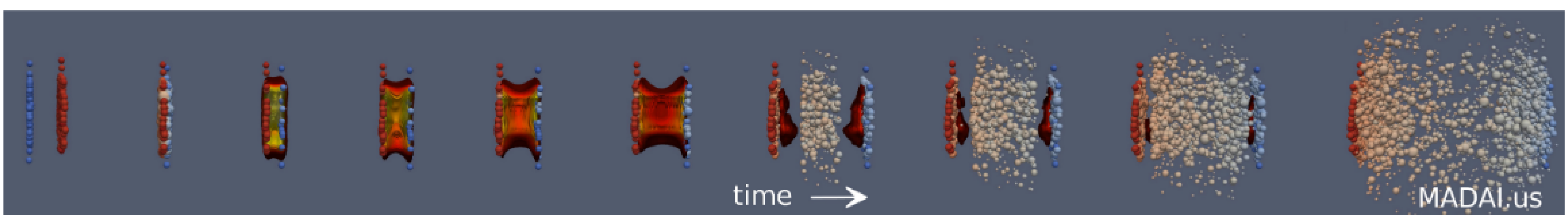
- $\frac{s}{T^3} = 7$ Cleymans, Oeschler, Redlich & Wheaton. Phys. Lett. B 615, 50-54 (2005)

- $n_B + n_{\bar{B}} = 0.12\, fm^{-3}$ Braun-Munzinger & Stachel. J. Phys. G 28, 1971-1976 (2002)

- $n(T, \mu_B) = \frac{1.24}{V_h}\left[1 - \frac{n_B(T, \mu_B)}{n(T, \mu_B)}\right] + \frac{0.34}{V_h}\left[\frac{n_B(T, \mu_B)}{n(T, \mu_B)}\right]$ Magas & Satz. Eur. Phys. J. C 32 115 (2003)

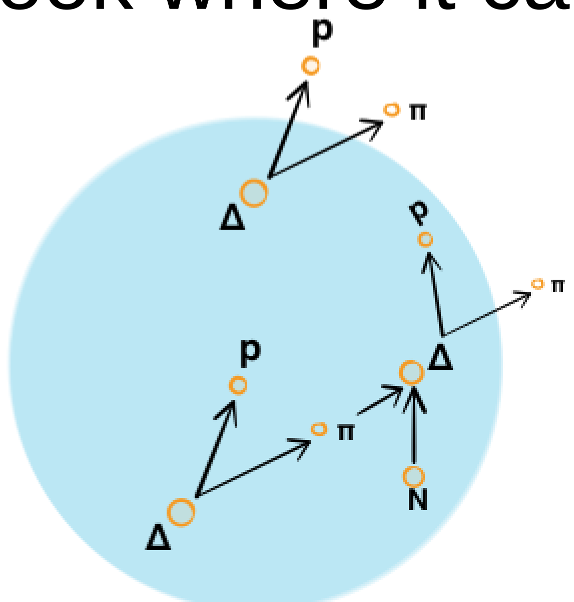
UrQMD

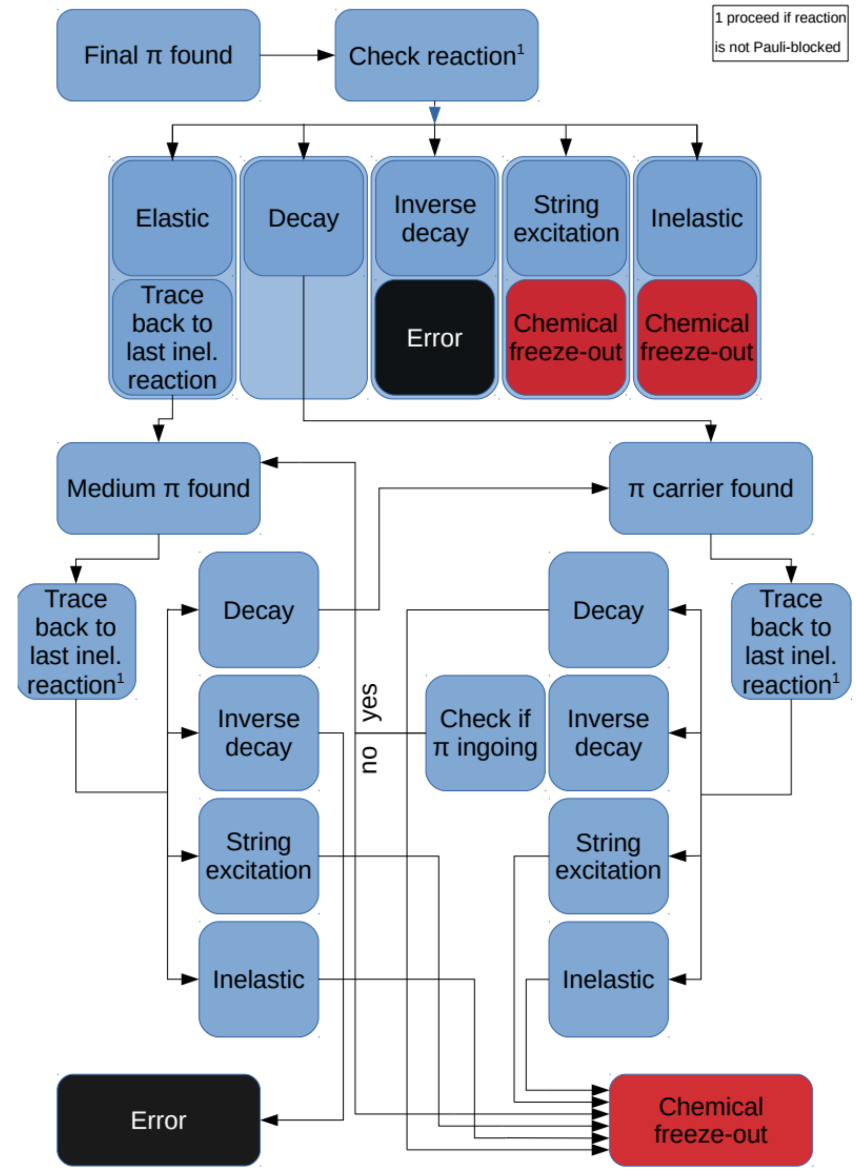
- Ultra-relativistic Quantum Molecular Dynamics
- Hadronic transport simulation
- Mesonic & Baryonic resonances up to 2 GeV
- Cross sections from experimental data
- Strangeness exchange reactions
- Very succesfull



The reconstruction

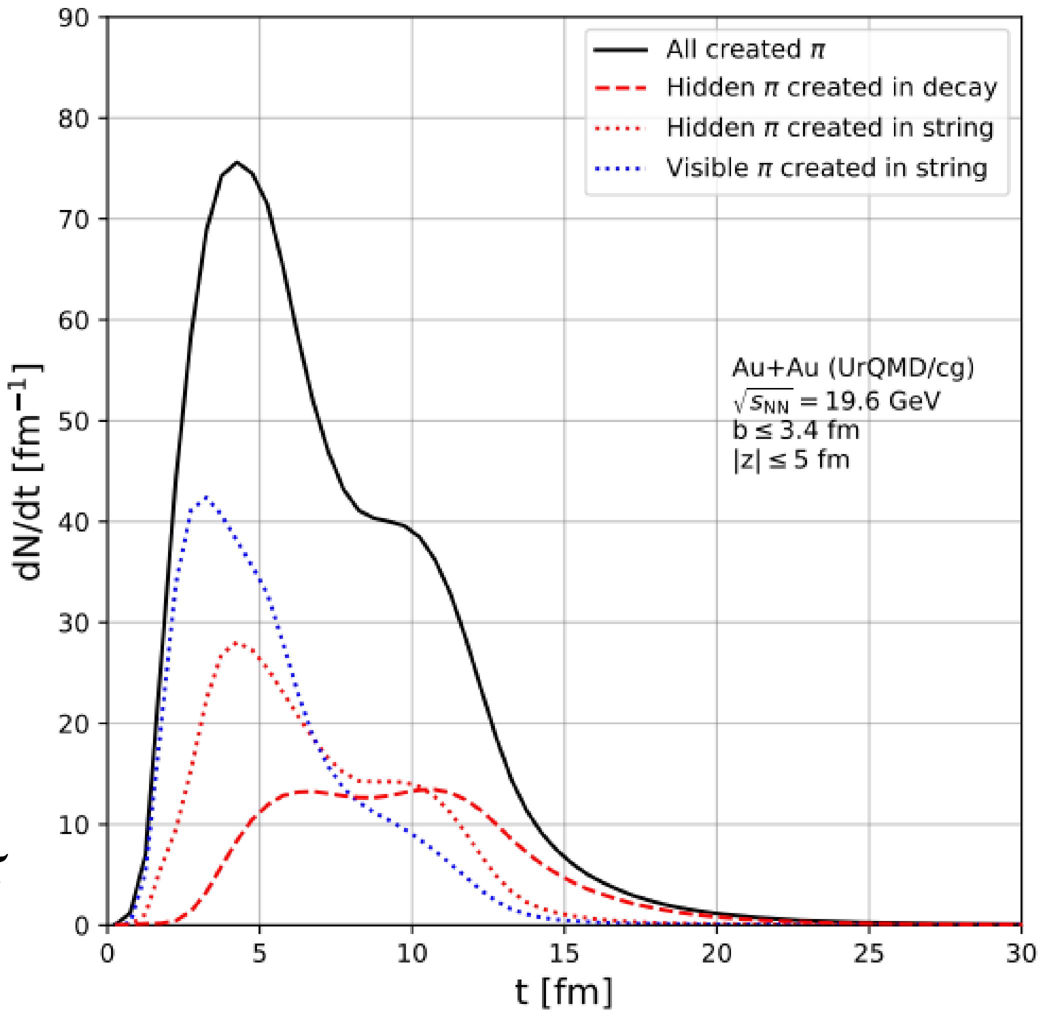
- Idea: π+N ↔ Δ doesn't affect π number!
- Find π at kinetic freeze-out
- Look where it came from





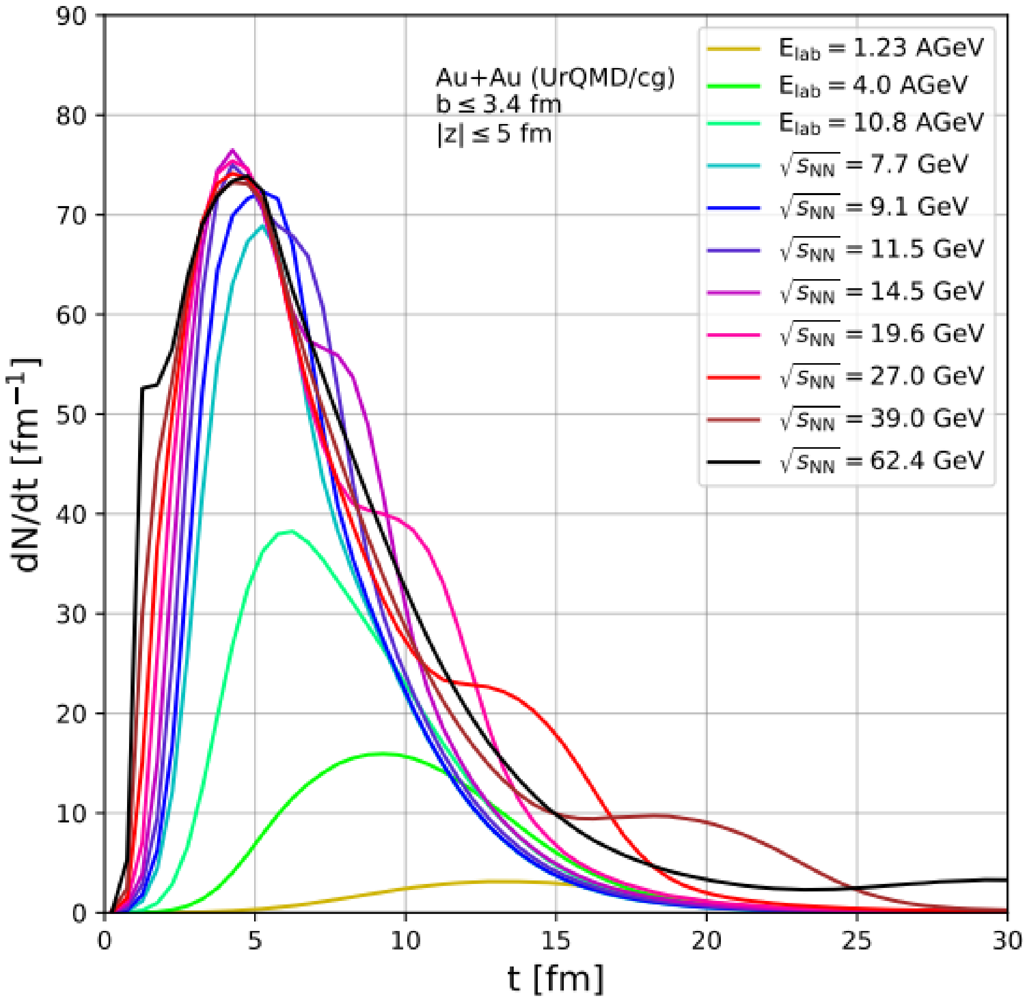
Freeze-out times

- 5 fm: local max.
  - Mostly strings
  - Some decays
- 10 fm: bump
  - Decays & strings
  - E.g.: $N^* \rightarrow N + \rho$
    $\rightarrow N + \pi + \pi$



Freeze-out times

- Above $\sqrt{s_{NN}}=7\,\text{GeV}$ maxima centered at 5-7 fm
- Narrow distribution



Coarse graining

- Calculate energy-momentum tensor in cells with $\Delta x = \Delta y = \Delta z = 1$ fm and $\Delta t = 0.25$ fm/c

$$T^{\mu\nu}(t,\vec{r}) = \frac{1}{\Delta V} \left\langle \sum_{i=1}^{N_h \in \Delta V} \frac{p_i^{\mu} p_i^{\nu}}{p_i^0} \right\rangle$$

- Calculate net-baryon current

$$j_B^{\mu}(t,\vec{r}) = \frac{1}{\Delta V} \left\langle \sum_{i=1}^{N_h \in \Delta V} B_i \frac{p_i^{\mu}}{p_i^0} \right\rangle$$

- 4-velocity from Eckart's frame definition

$$u^{\mu} = j_B^{\mu} \cdot \left(\sqrt{j_B^{\nu} j_{B,\nu}}\right)^{-1} = (\gamma, \gamma\vec{v})$$

Coarse graining

- We obtain: $\rho_B = j^0_{B,LRF}$ & $\varepsilon = T^{00}_{LRF}$
- Rescale ε to account for pressure anisotropy

$$\varepsilon_{corr} = \varepsilon / r(\chi)$$

with $$r(\chi) = \begin{cases} \frac{\chi^{-1/3}}{2}\left[1 + \frac{\chi \,\mathrm{artanh}\left(\sqrt{1-\chi}\right)}{\sqrt{1-\chi}}\right] & \text{if} \quad \chi < 1 \\ \frac{\chi^{-1/3}}{2}\left[1 + \frac{\chi \arctan\left(\sqrt{\chi-1}\right)}{\sqrt{\chi-1}}\right] & \text{if} \quad \chi > 1 \end{cases}$$

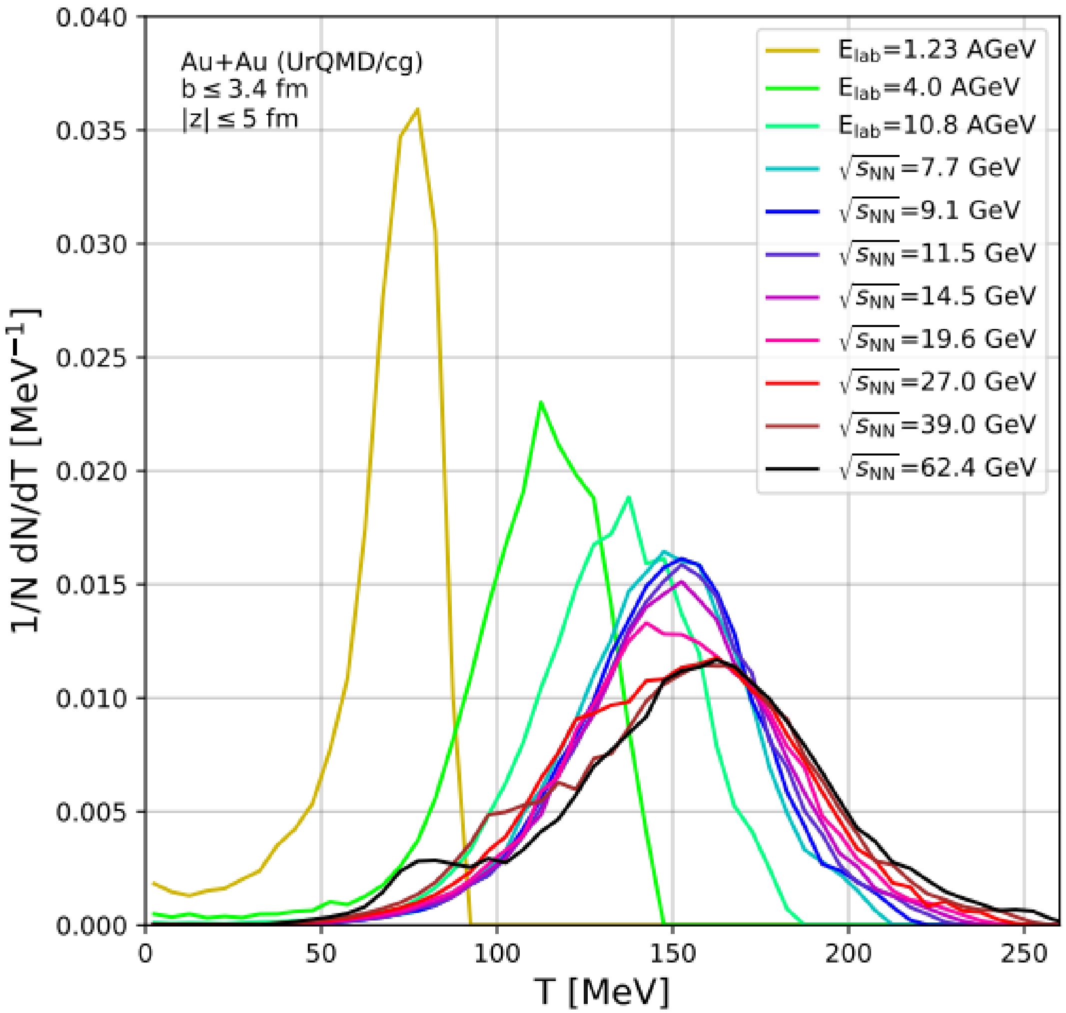
and $\chi = \left(P_\perp / P_\parallel\right)^{4/3}$

Florkowski and Ryblewski. Phys. Rev. C 83 (2011) 034907

- Interpolate HRG EoS to obtain: $T(\varepsilon_{corr}, \rho_B), \mu_B(\varepsilon_{corr}, \rho_B)$

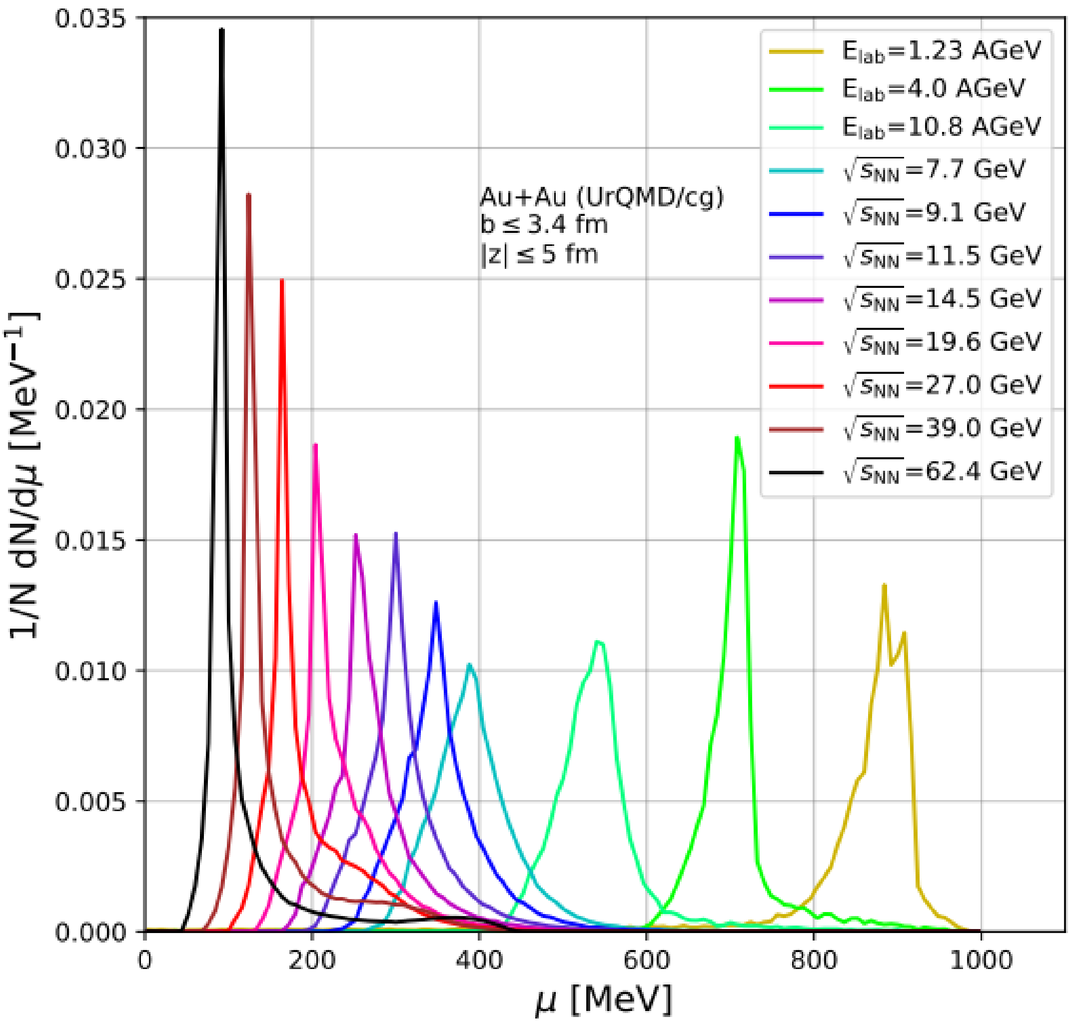
Freeze-out temperatures

- T_{max} & $\langle T \rangle$ saturate at 150 MeV
- Symmetric distribution above $\sqrt{s_{NN}} = 7$ GeV
- FWHM ≈ 50 MeV

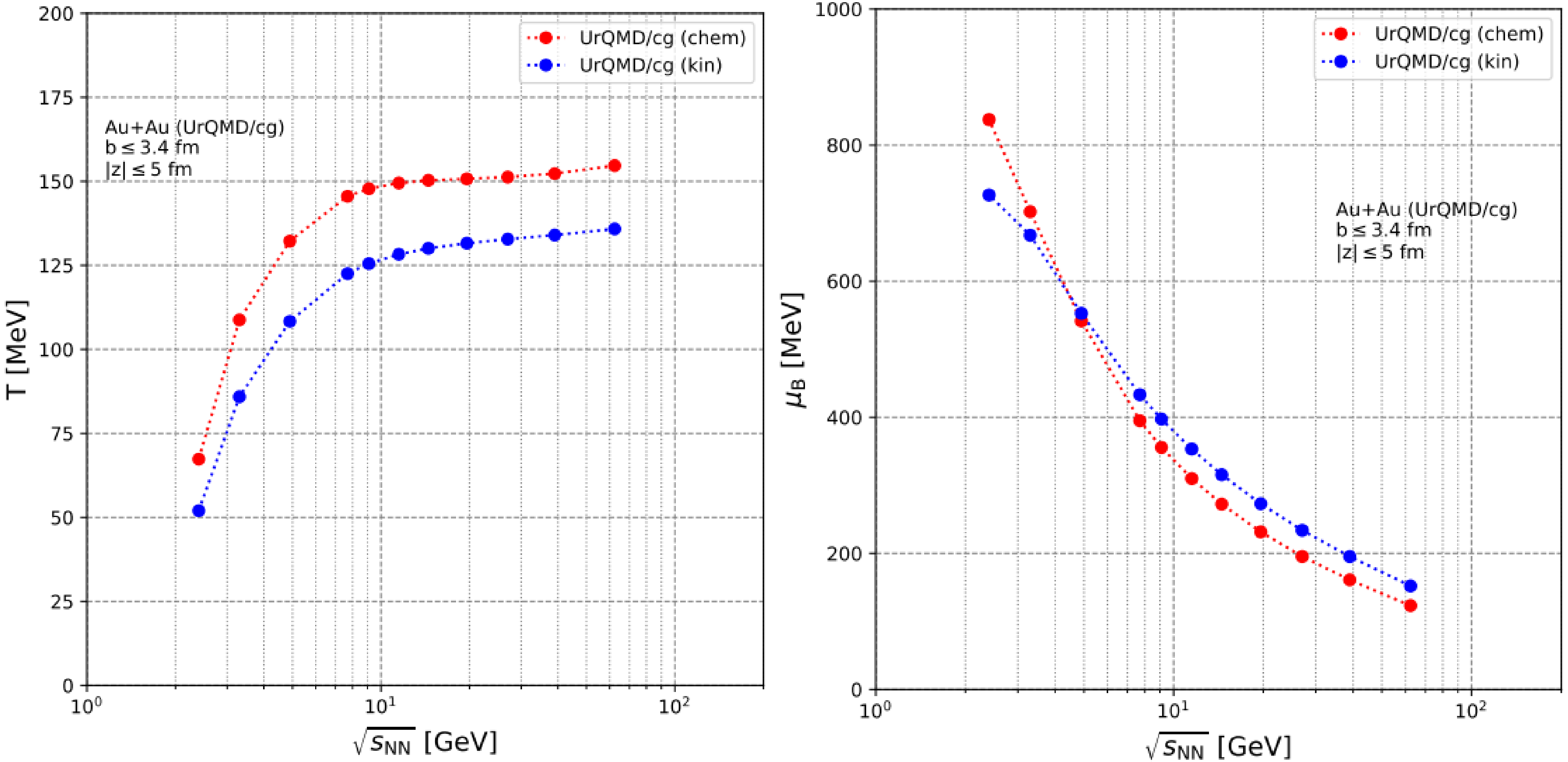


Freeze-out baryo-chemical potentials

- $\langle \mu_B \rangle$ decreases with increasing $\sqrt{s_{NN}}$
- Increasing $\overline{B}$/B ratio towards higher $\sqrt{s_{NN}}$



Energy dependence of $\langle T \rangle$ & $\langle \mu_B \rangle$



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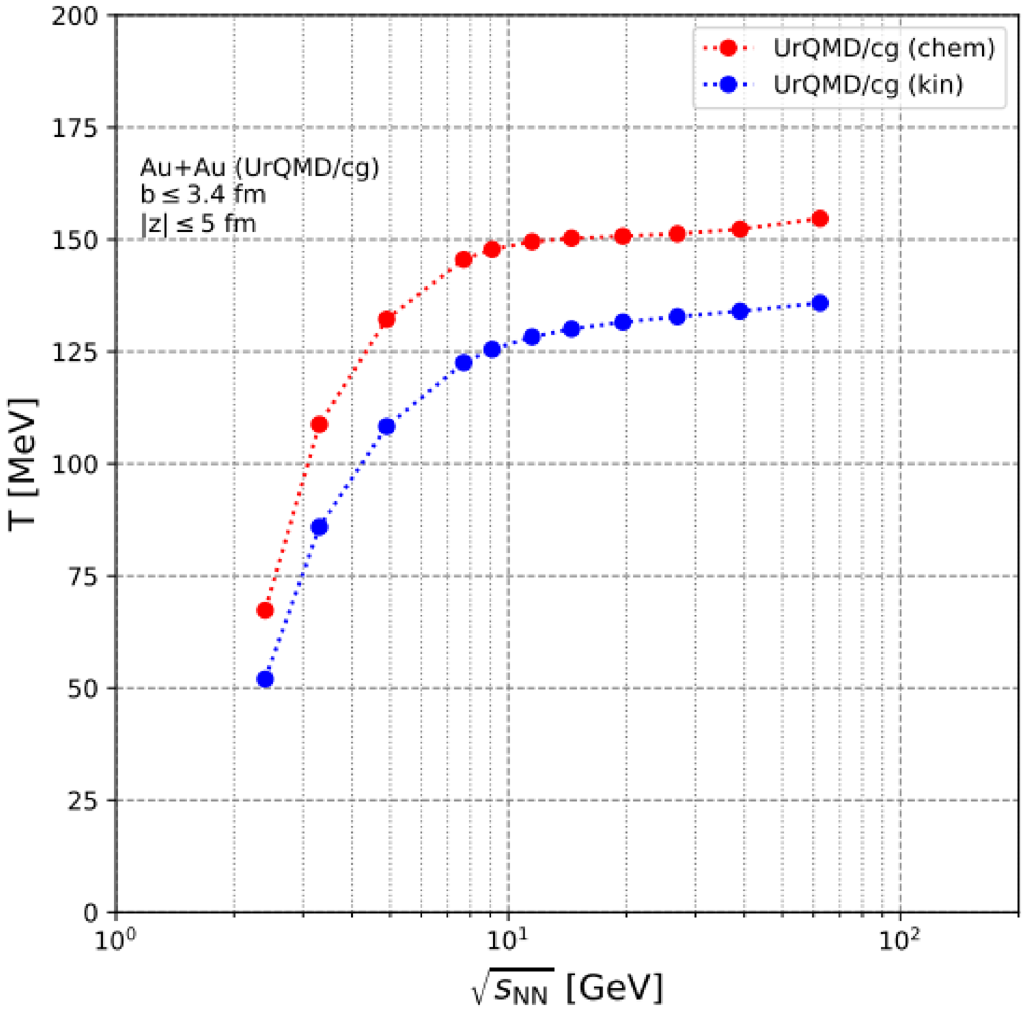
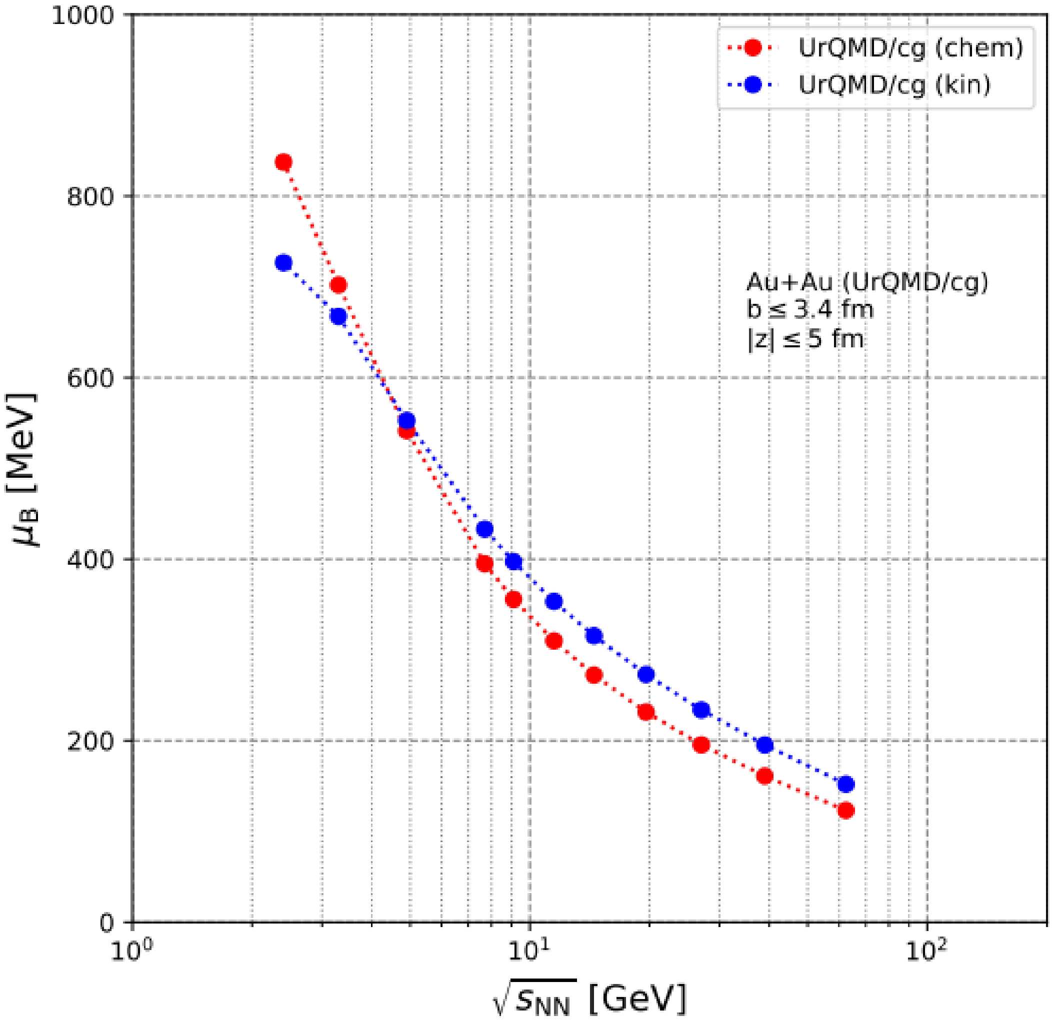
Energy dependence of $\langle T \rangle$ & $\langle \mu_B \rangle$



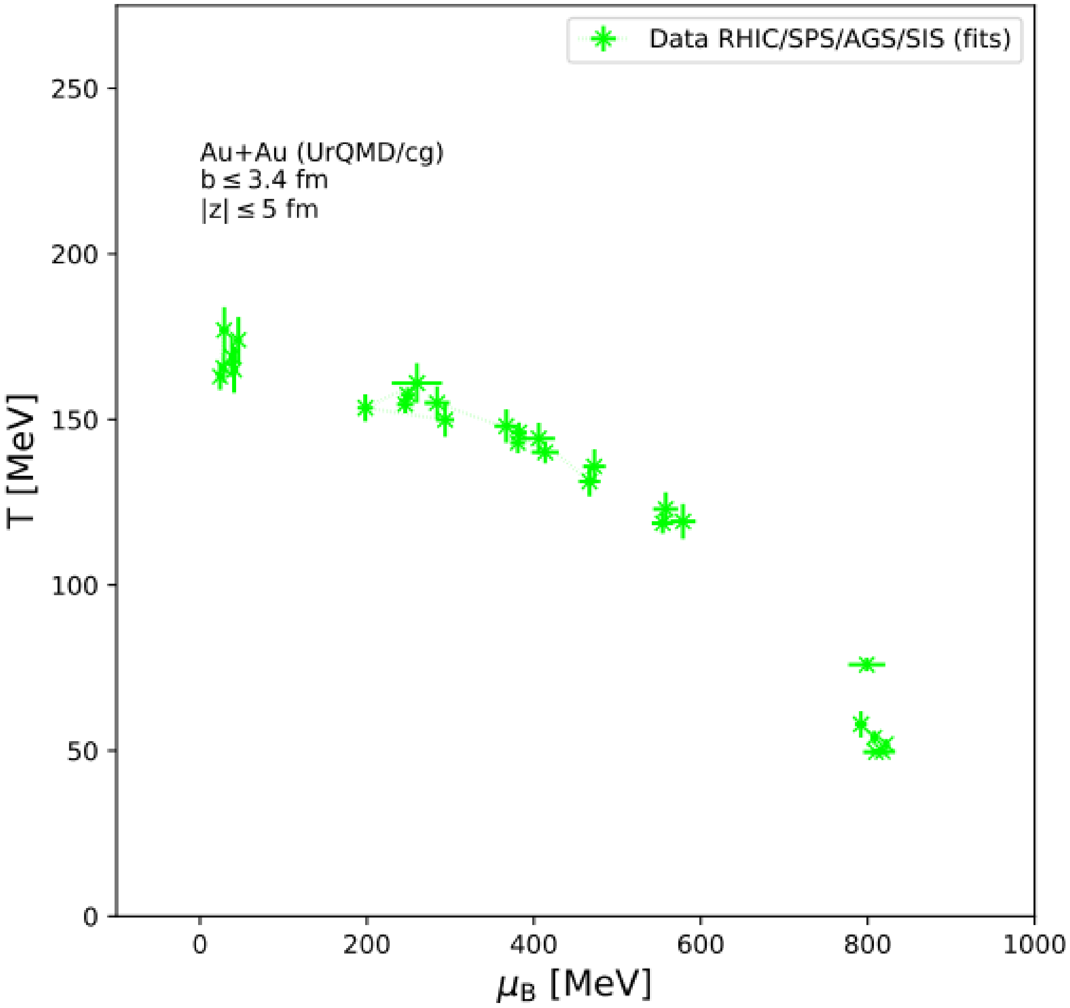
- $T_{chem} - T_{kin} > 0$ implies that indeed $t_{chem} < t_{kin}$
- $\Delta T \approx 20 \pm 5$ MeV
- Saturation at 150 MeV (chem.)
- Saturation at 130 MeV (kin.)

Energy dependence of $\langle T \rangle$ & $\langle \mu_B \rangle$

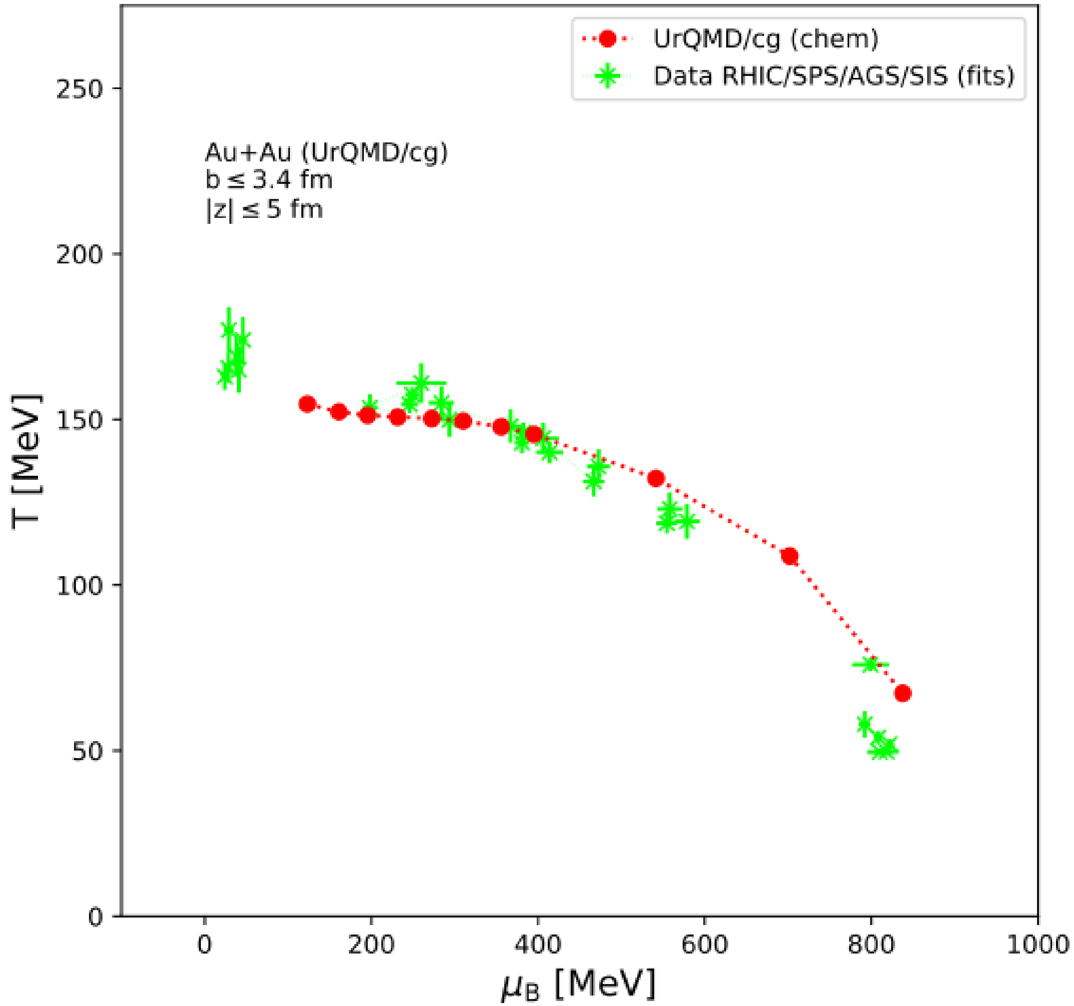
- Both decrease rapidly
- $\mu_B \rightarrow 0$ MeV at LHC
- $\mu_B^{chem} \approx \mu_B^{kin}$



Phase diagram

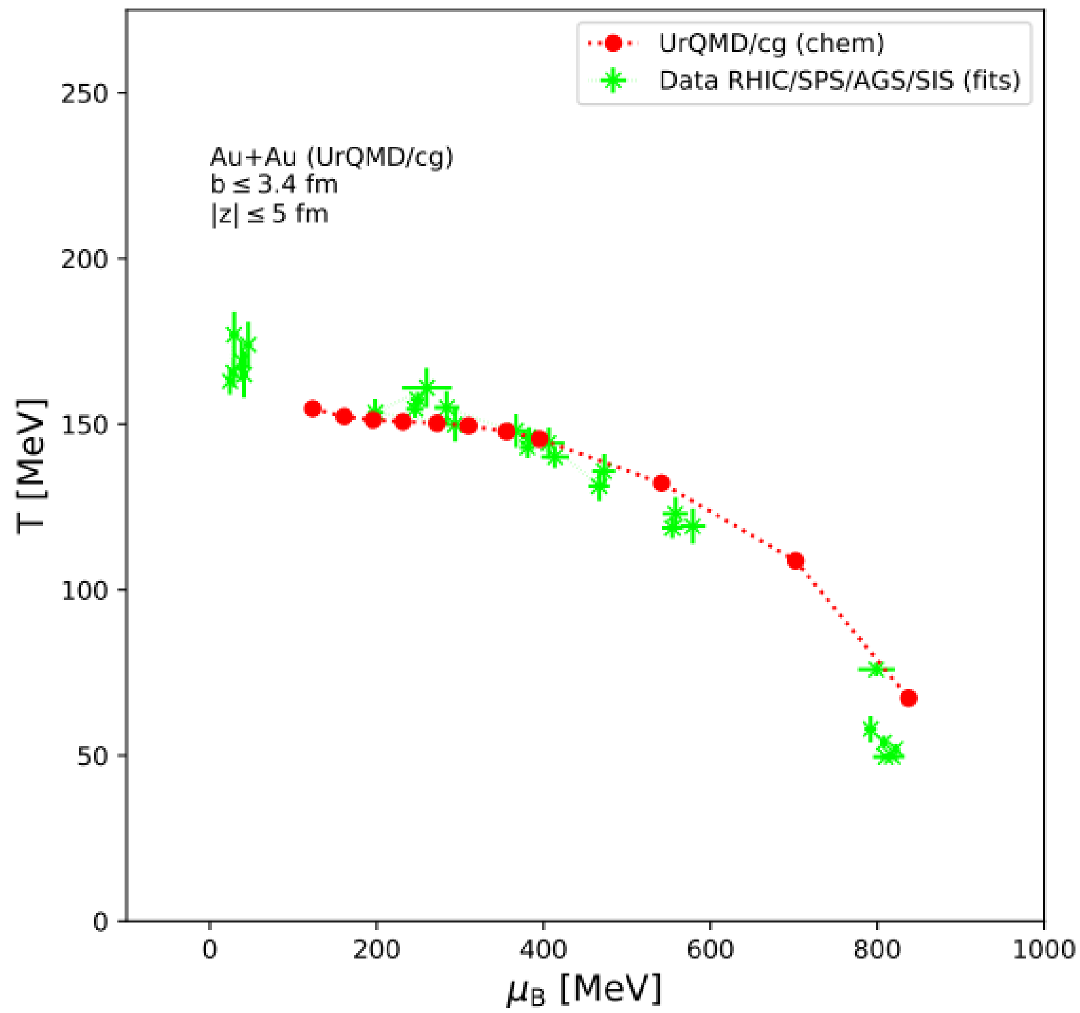


Phase diagram



Phase diagram

- Description good from SIS to RHIC
- But, UrQMD does neither involve a QGP nor a chem. break up
- How does this work?



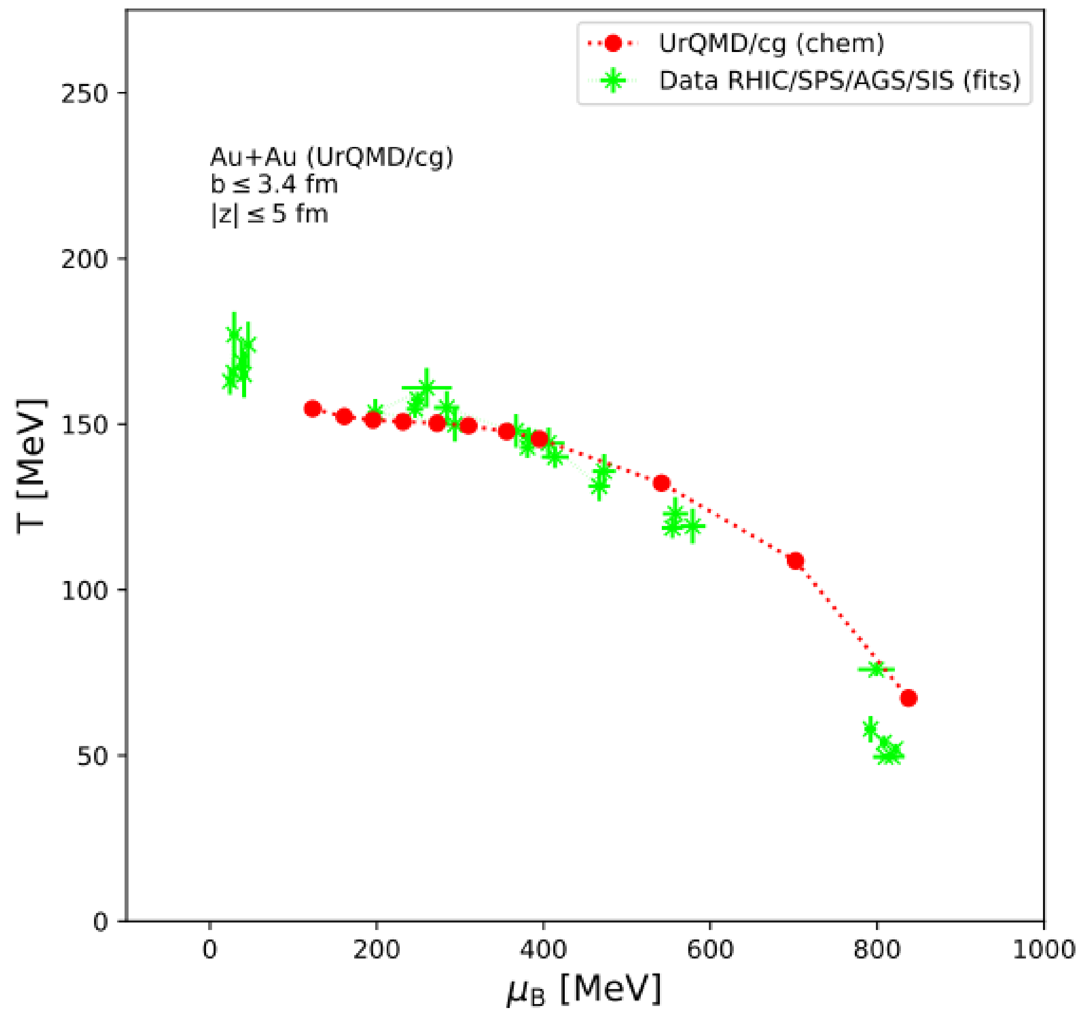
Phase diagram

Equilibrium ≡ scattering rate Γ > expansion rate Θ

- Knudsen number

$$Kn = \frac{\Theta}{\Gamma} \sim \frac{\partial_\mu u^\mu}{f_i f_j \sigma^{ij}}$$

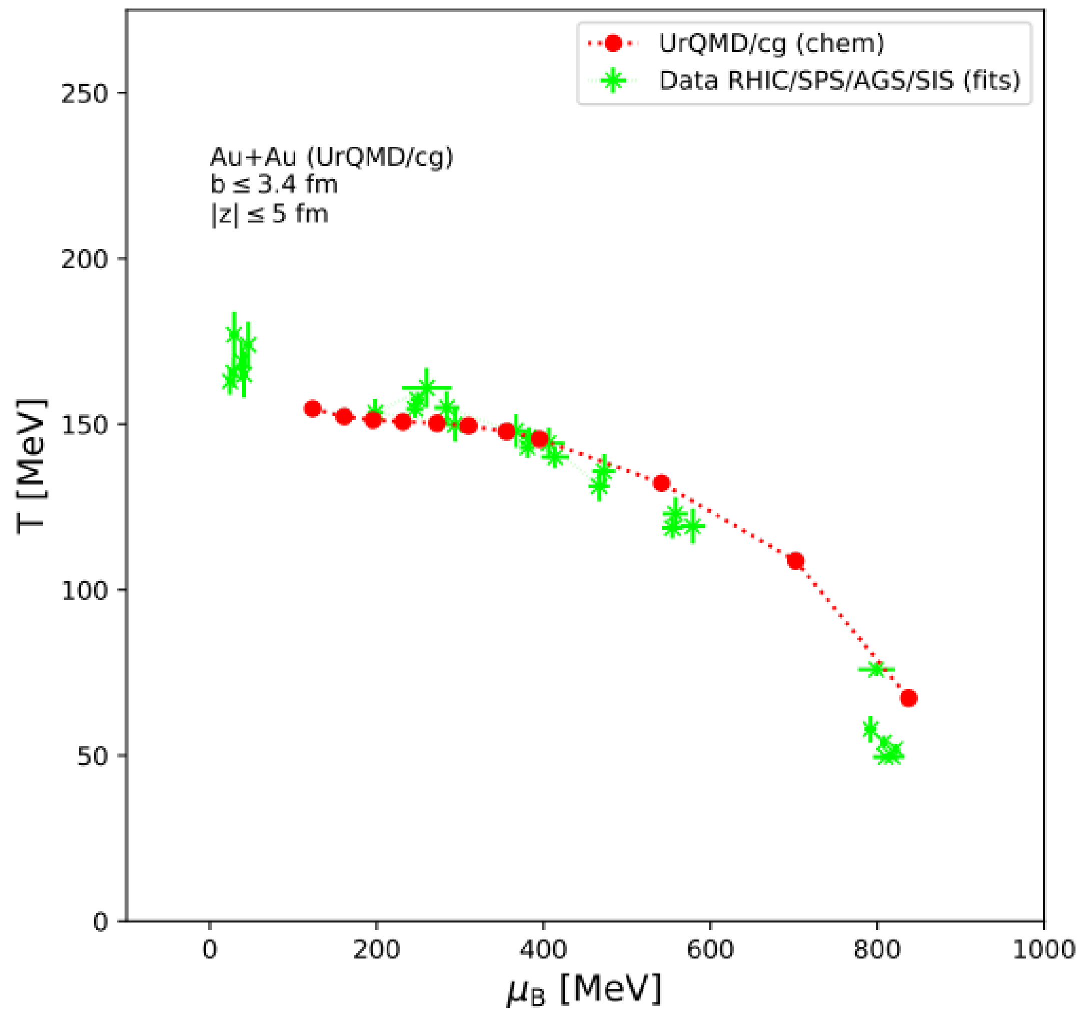
- f: phasespace density
- σ: inel. cross section
- u^μ: 4-velocity



Phase diagram

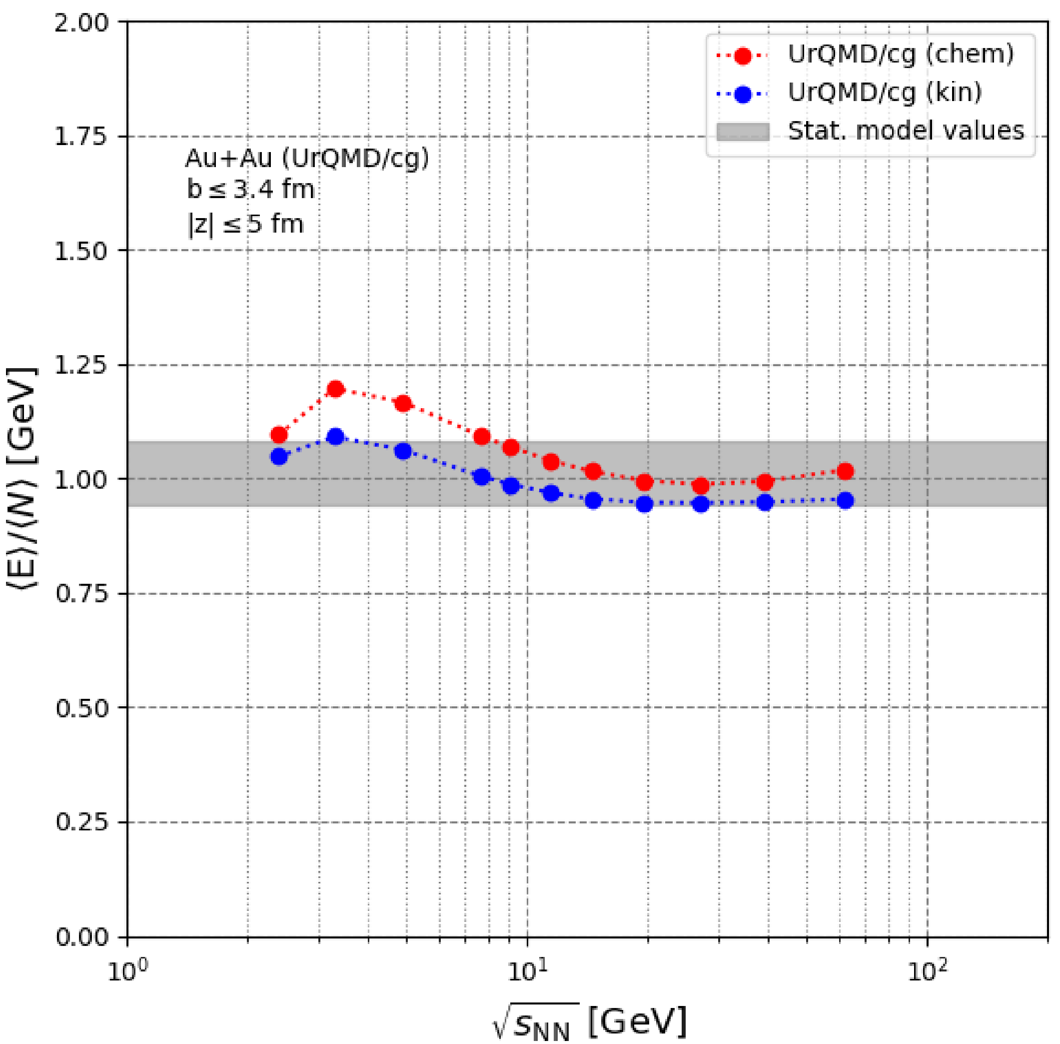
Chemical freeze-out in UrQMD:

- Local interplay of Γ and Θ
- Not related to the phase transition from QGP to HG!
- Further evidence through freeze-out criteria



Average energy per particle

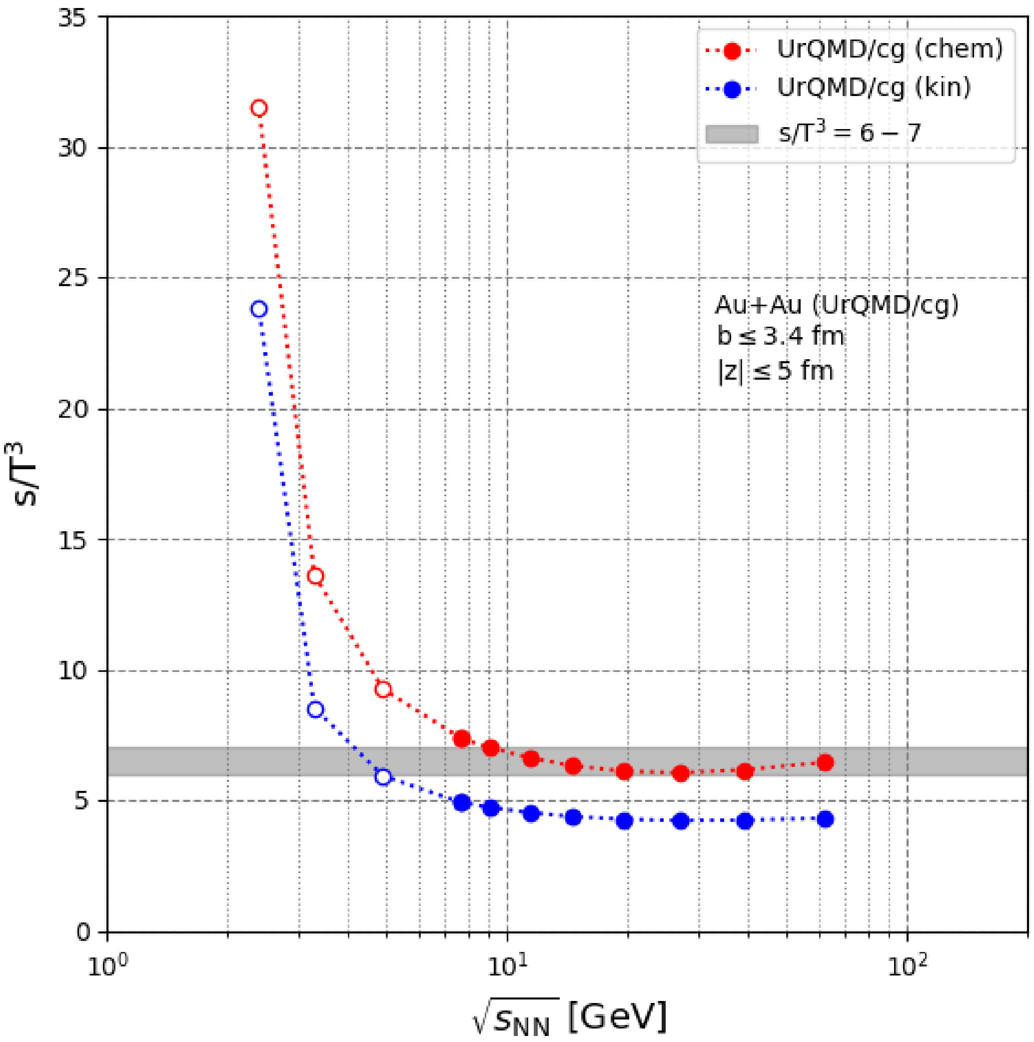
- In line with stat. model up to 20%
- Slight energy dependence
- Kinetic freeze-out also at 1 GeV/particle



Entropy density

- Effective d.o.f.
- s/T^3 (chem.) ≈ 6-7 &

  s/T^3 (kin.) ≈ 4-5 confirmed above $\sqrt{s_{NN}} = 7\,\text{GeV}$
- Switch from baryon-dominated to meson-dominated regime



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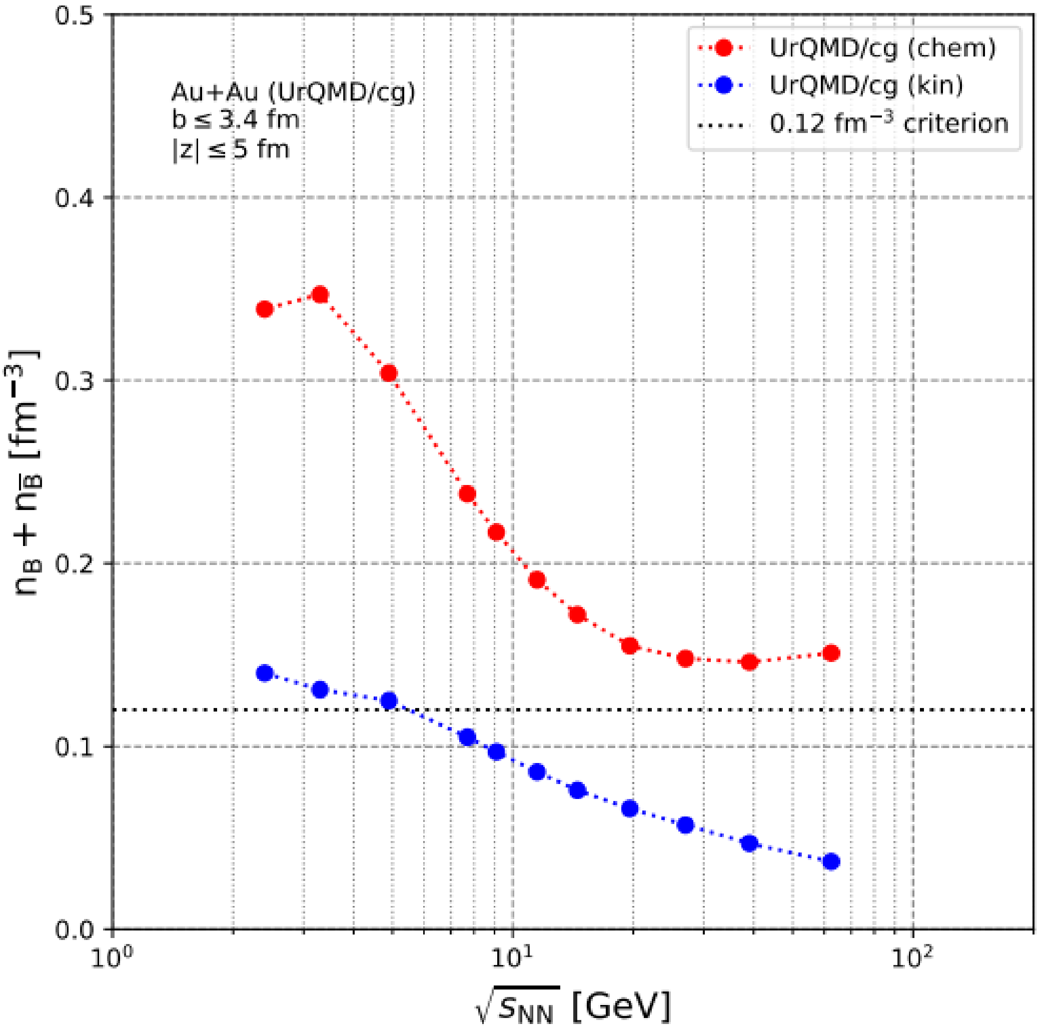
Total baryon density

- $n_B+n_{\bar{B}}$ (chem.) ≈ 0.15 fm^{-3} confirmed above $\sqrt{s_{NN}}=20$ GeV
- Stronger energy dependence … s/T^3 and E/N better!



Summary

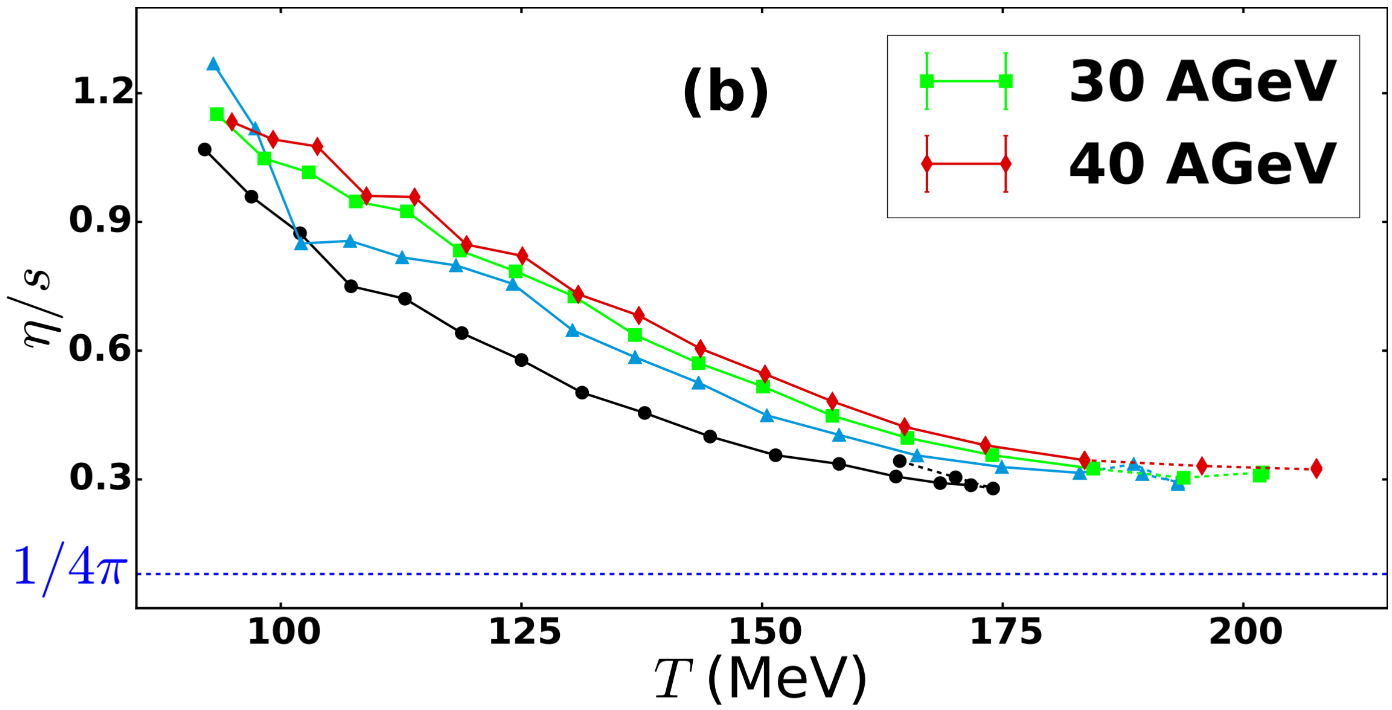
- Novel approach to determine the chemical freeze-out hyper-surface from a microscopic transport simulation
- Average chem. break up time: $\langle t_{chem} \rangle \approx 7$ fm/c
- $\langle T \rangle$ & $\langle \mu_B \rangle$ match stat. model results
- Chem. freeze-out is connected to scattering dynamics and not to deconfinement
- Confirm freeze-out criteria: E/N, s/T^3 and $n_B + n_{\bar{B}}$

Backup – η/s

- η/s: shear viscosity to entropy density ratio
- Quantifies system's resoponse to shear perturbation
- Ideal fluid $\eta/s \rightarrow 0$
- RHIC: $\eta/s \rightarrow (4\pi)^{-1} \rightarrow$ QGP perfect fluid
- Usually extracted by fitting v_2 from hydrodynamics simulations to data
- Highly viscous hydrodynamics numerically not solvable

Backup – η/s

- Use UrQMD/cg to extract η/s at E_{lab}=1.23 AGeV
- Interpolate η/s(T) from *Teslyk et al. Phys.Rev. C101 (2020) no.1, 014904*

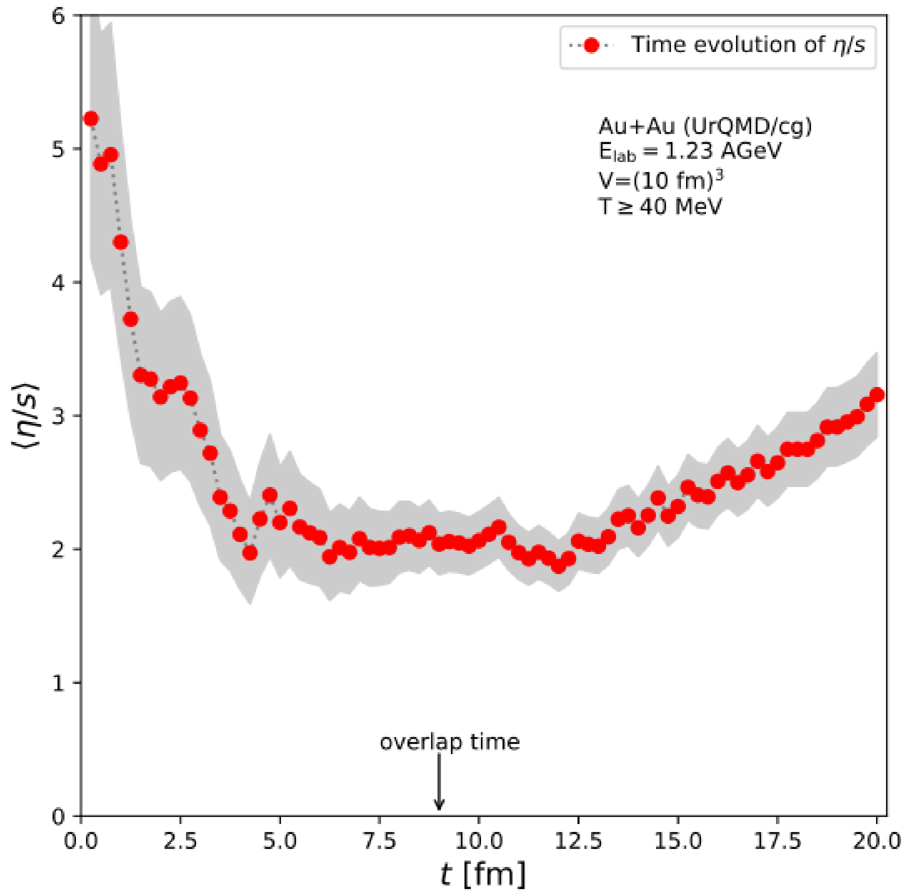


Teslyk et al. Phys.Rev. C101 (2020) no.1, 014904

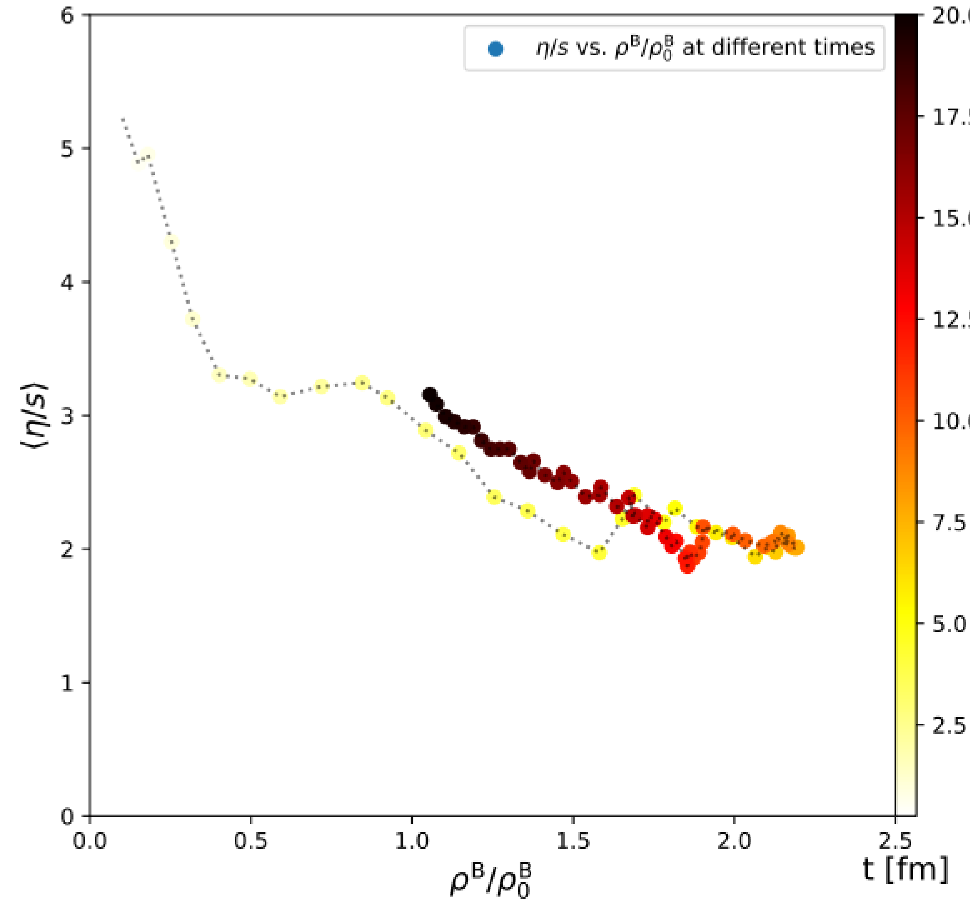
- $\eta/s(T)=0.0029\ \mathrm{GeV}^{2.5}\ T^{-2.5}$

Backup – η/s

- Time evolution

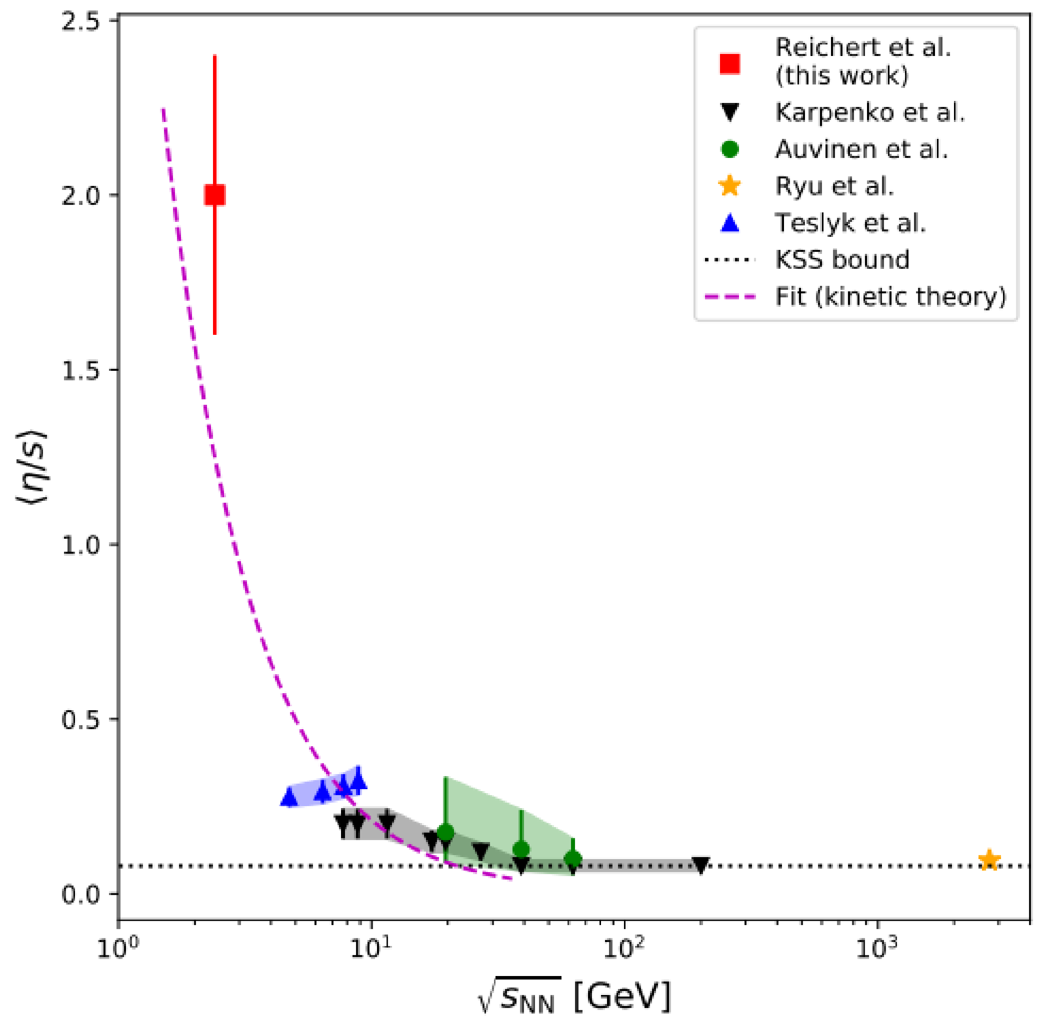


- Density dependence



Backup – η/s

- Energy dependence
- Low energies: η/s of a hadron gas
- High energies: η/s of a perfect fluid



Thank you for your attention!

Questions?

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Further reading:

- T. Reichert, G. Inghirami & M. Bleicher
  Eur. Phys. J. A 56 (2020) 10, 267
- T. Reichert, G. Inghirami & M. Bleicher
  arXiv: 2011.04546