In-medium effects in strangeness production in heavy-ion collisions at (sub-)threshold energies

Elena Bratkovskaya

(GSI Darmstadt & Uni. Frankfurt)

in collaboration with

Taesoo Song, Laura Tolos, Joana Wirth, Jörg Aichelin

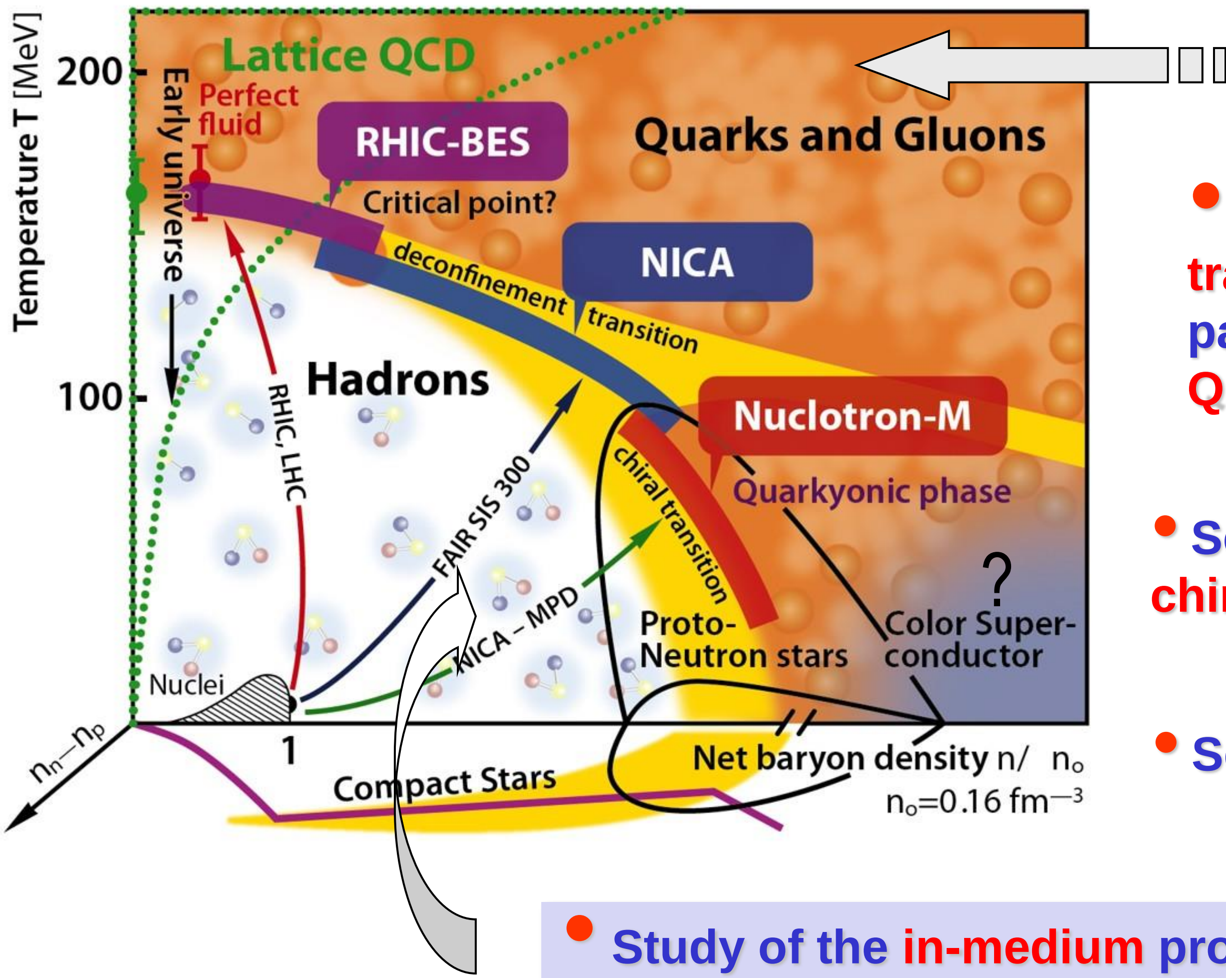
(GSI, Barcelona Uni., TU München, SUBATECH)

10th International Conference on New Frontiers in Physics (ICNFP 2020)

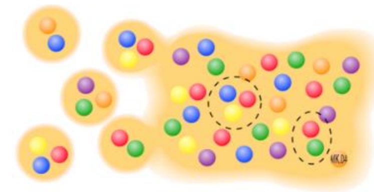
Kolymbari, Greece, 23 August - 3 September 2021

The ‚holy grail‘ of heavy-ion physics:

The phase diagram of QCD



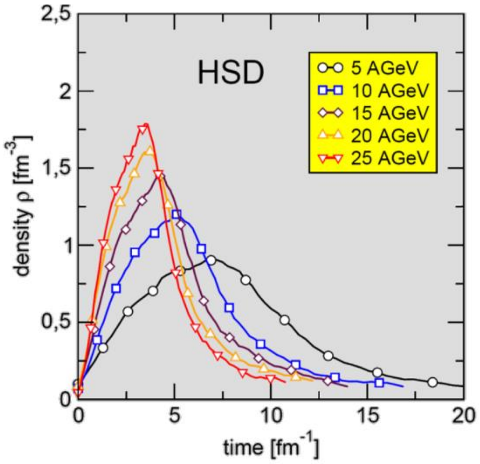
- Search for the critical point



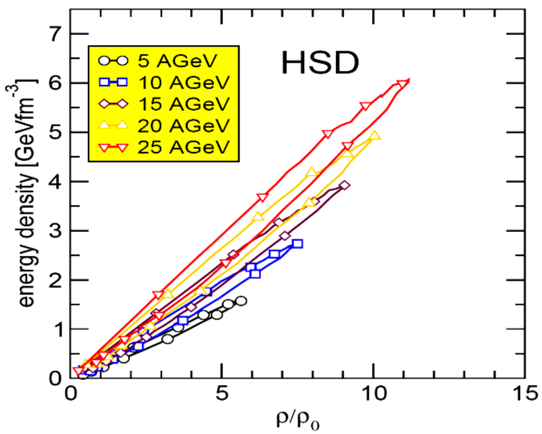
- Study of the phase transition from hadronic to partonic matter – Quark-Gluon-Plasma
- Search for signatures of chiral symmetry restoration
- Search for the critical point
- Study of the in-medium properties of hadrons at high baryon density and temperature

Dense and hot matter created in HICs

Time evolution of baryon density ρ



Energy density vs. ρ/ρ_0

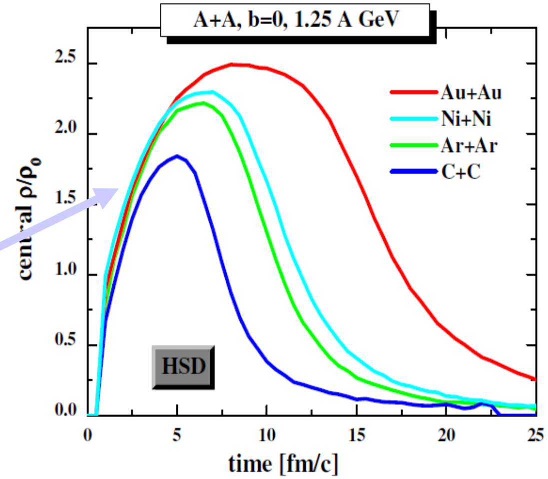


Large energy and baryon densities (even above critical $\varepsilon > \varepsilon_{crit} \sim 0.5$ GeV/fm³) are reached in the central reaction volume at CBM and BM@N/NICA energies (> 5 A GeV)
➔ a phase transition to the QGP

❑ **At SIS energies: baryon density in central A+A collisions at 1.25 A GeV:**

- **increases with nuclear size up to 2.5 ρ_0**
- **the reaction time is larger for heavy systems**

➔ Highly dense matter is created already at SIS energies!



In-medium effects

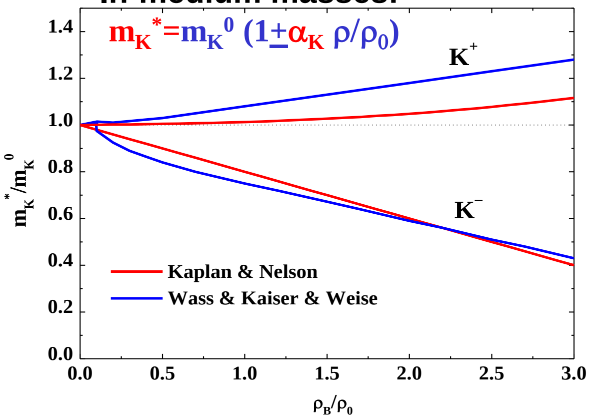
The hadrons - in particular strange mesons (K, Kbar and K*) - modify their properties in the dense and hot nuclear medium due to the strong interaction with the environment

Models:

- chiral SU(3) model, chiral perturbation theory, relativistic mean-field models: KN-potential ➔ 'dropping' of K^- mass and 'enhancement' of K^+ mass

Kaplan and Nelson, PLB 175 (1986) 57;
Weise, Brown, Schaffner, Krippa, Oset, Lutz, Mishra, ... et al.

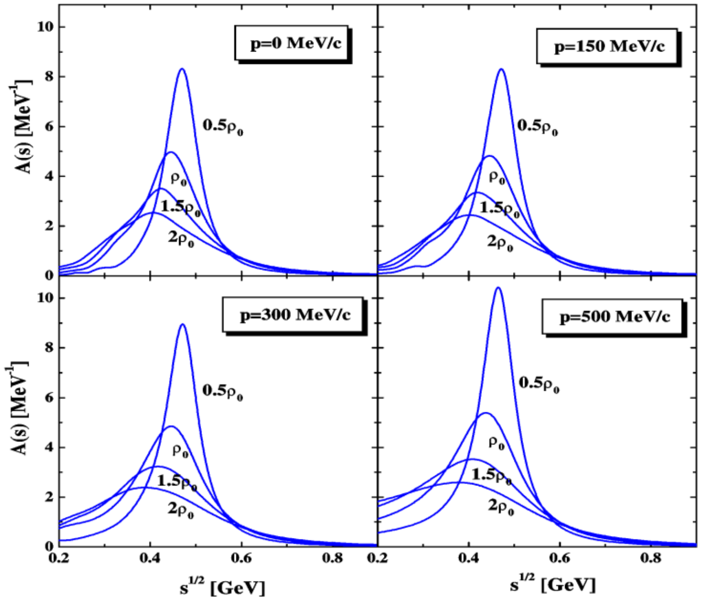
In-medium masses:



- self-consistent coupled-channel approach - G-matrix:

➔momentum, density and temperature dependent spectral function of antikaons $A(p_K,\rho,T)$:
in-medium modification of the real and imaginary part of the self-energy (mass and width)

Tolos et al., NPA 690 (2001) 547



Strangeness production in NN vs. AA

- How to observe experimentally in-medium effects in strangeness production?
- How to quantify K^+,K^- in-medium properties (potentials and spectral functions)?

→ Study **strange meson (K, Kbar) production in A+A at (sub-)threshold energies**

NN collisions:

NN → NNK^+K^-

NN → NYK^-

no K^+,K^- production if $s^{1/2} < s^{1/2}_{th}$

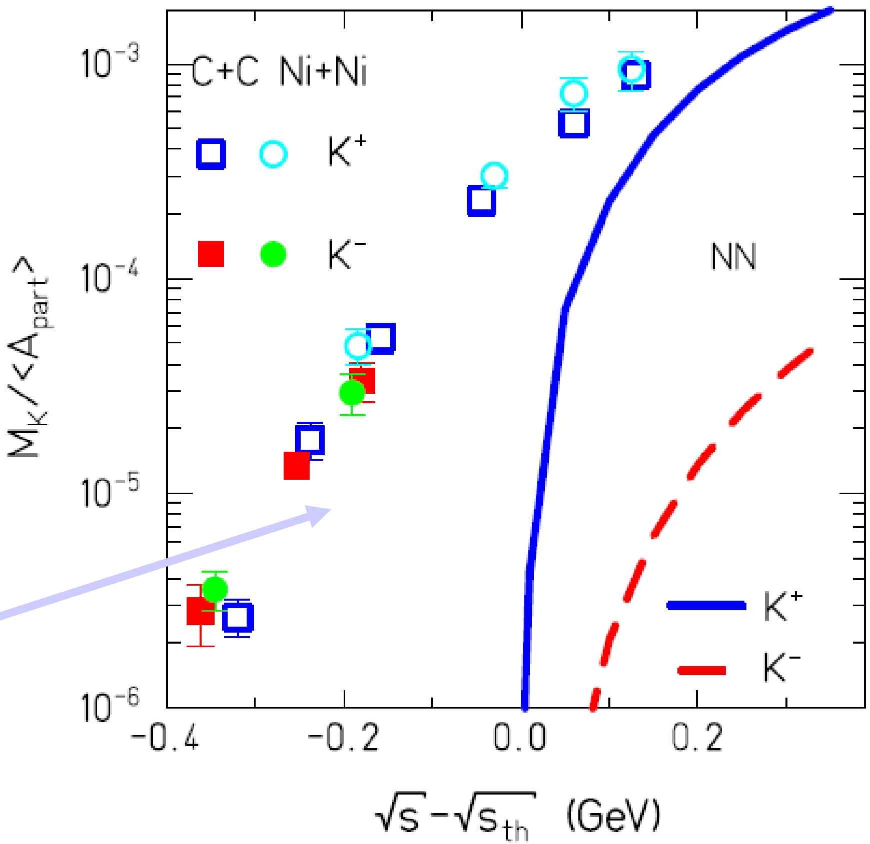
E.g.:

N+N → N+Λ+K^+ requires

$\Delta E = 2M_N - (M_K + M_\Lambda + M_N) = 670$ MeV

AA collisions:

experimental observation of K^+,K^- production below the NN-threshold !



Plot by C. Hartnack

Near threshold strangeness production in AA

I. Strangeness production channels at low energies

- **baryon-baryon collisions:**

$$B + B \rightarrow B + Y + K$$

$$B + B \rightarrow B + B + K + \overline{K}$$

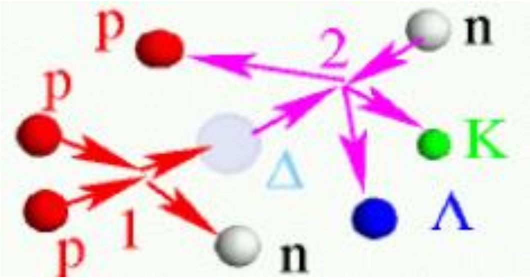
$$B + Y \rightarrow B + B + \overline{K}$$

$K = (K, K^0)$

$\overline{K} = (K^-, \overline{K}^0)$

$B = (N, \Delta, ...)$

$Y = (\Lambda, \Sigma)$



Plots by C. Hartnack

- **meson-baryon collisions:**

$$\pi + B \rightarrow Y + K$$

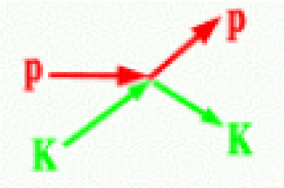
$$\pi + B \rightarrow B + K + \overline{K}$$

$$\boxed{\pi + Y \rightarrow B + \overline{K}}$$

→ dominant channel for low energy K^- production!

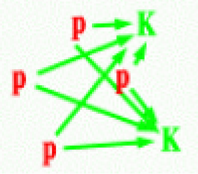
- **meson-meson collisions:** $\pi + \pi \rightarrow K + \overline{K}$

- **resonance decays:** $K^* \rightarrow \pi + K, ...,$ $\phi \rightarrow K + \overline{K}$ ...,



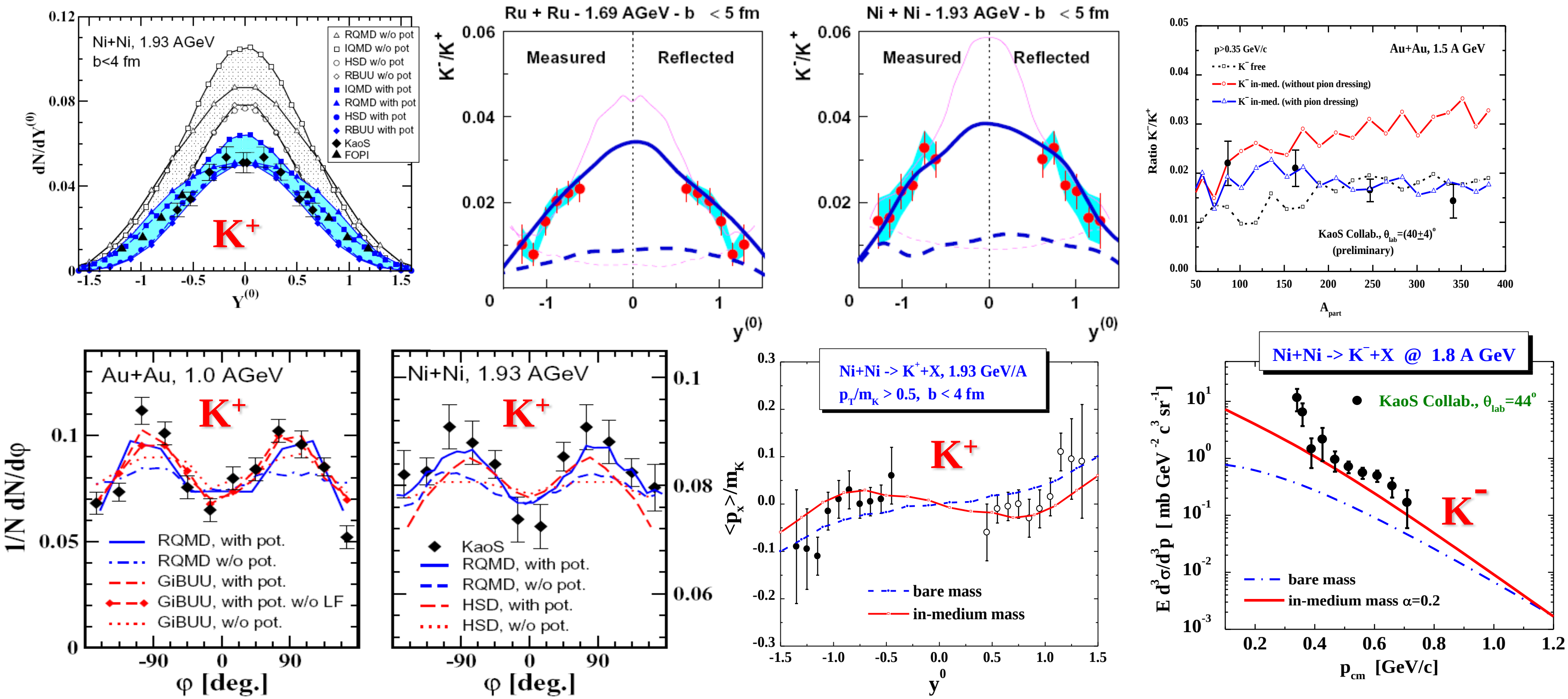
II. Strangeness rescattering

= (quasi-)elastic scattering with baryons and mesons



The production cross sections and self-energies of K, Kbar are modified in the nuclei medium !

Transport models vs. experimental data - highlights



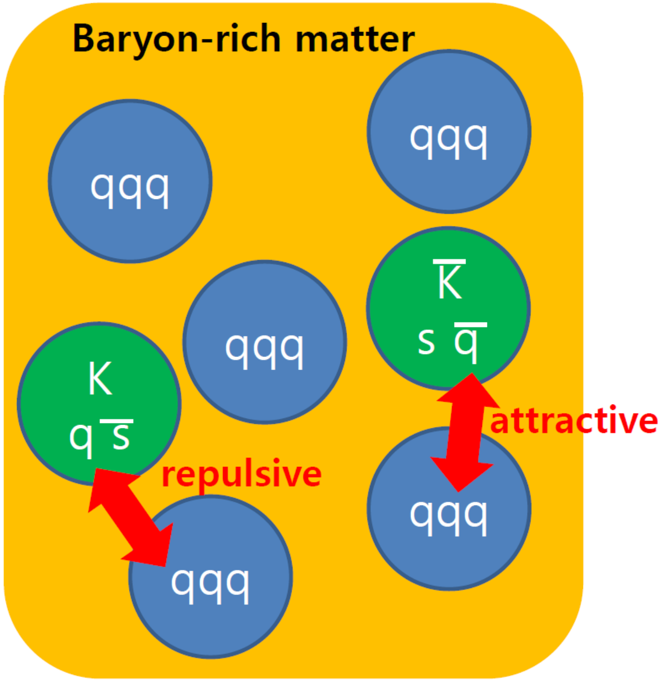
Heavy-ion experiments at SIS energies (FOPI, KaoS, HADES):

Observables: invariant yield, rapidity spectra, ratios, flow, angular distr. ➔

- **Moderate repulsive potential for K^+**
- **Stronger attractive potential for K^-**

- Is it a final answer?!
- No! A consistent theoretical description of the variety of observables is not yet achieved!

In-medium effects:
I. Kaons – repulsive potential
II. Antikaons – G-matrix



I. Kaons - repulsive potential

- modification of kaons K=(K^+, K^0) in the dense and hot medium:

Repulsive potential in nuclear matter:

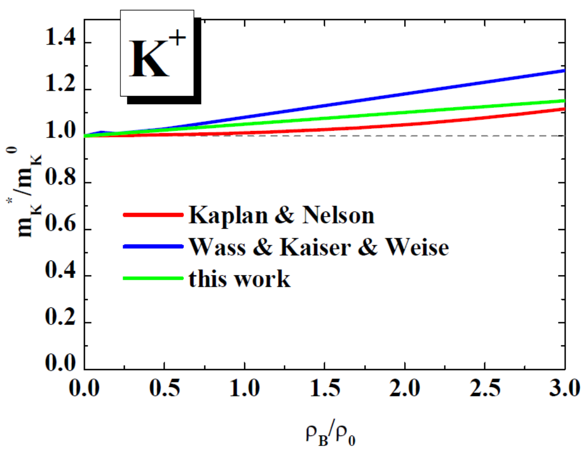
$$V_K = 25\text{ MeV} \times (\rho/\rho_0)$$

Single-particle energy of the kaon in nuclear matter is approximated in the nonrelativistic limit by

$$\mathcal{E} = \sqrt{m_K^2 + p^2 + \text{Re}\,\Sigma} \simeq E_K + \frac{\text{Re}\,\Sigma}{2E_K} = E_K + V_K$$

V_K is related to **an increase of the effective mass**:

$$m_K^* = \sqrt{m_K^2 + \text{Re}\,\Sigma} = \sqrt{m_K^2 + 2E_K V_K}$$
$$\simeq m_K\left(1 + \frac{E_K V_K}{m_K^2}\right) \simeq m_K\left(1 + \frac{25\text{ MeV}}{m_K}\frac{\rho}{\rho_0}\right)$$



II. Antikaons: a coupled-channel G-matrix approach

- **modification of antikaons $\bar{K}$=(K^-,$\bar{K^0}$) in the dense and hot medium:**
  based on a self-consistent and unitary coupled-channel approach
  ➔ G-matrix (the latest edition*)

*** Improved!**

Basic ideas:
SU(3) meson-baryon chiral Lagrangian, which incorporates the *s-* and *p-* waves of the antikaon-nucleon interaction

$$L = \langle \bar{B} i\gamma^\mu \nabla_\mu B \rangle - M \langle \bar{B}B \rangle + \frac{1}{2} D \langle \bar{B}\gamma^\mu \gamma_5 \{u_\mu, B\} \rangle$$
$$+ \frac{1}{2} F \langle \bar{B}\gamma^\mu \gamma_5 [u_\mu, B] \rangle,$$

$$\nabla_\mu B = \partial_\mu B + [\Gamma_\mu, B],$$
$$\Gamma_\mu = \frac{1}{2}(u^\dagger \partial_\mu u + u\,\partial_\mu u^\dagger),$$
$$U = u^2 = \exp(i\sqrt{2}\Phi/f),$$
$$u_\mu = i u^\dagger \partial_\mu U u^\dagger,$$

Spin ½+ SU(3) baryon octet

$$B = \begin{pmatrix} \frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & \Sigma^+ & p \\ \Sigma^- & -\frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & n \\ \Xi^- & \Xi^0 & -\frac{2}{\sqrt{6}}\Lambda \end{pmatrix}$$

SU(3) pseudo-scalar meson octet

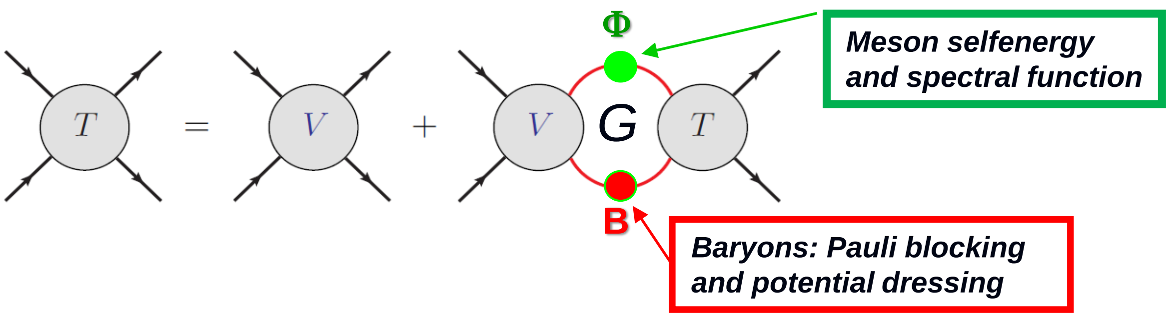
$$\Phi = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{pmatrix}$$

1) **1st G-matrix (based on the Jülich meson-exchange model): L. Tolos et al., NPA 690 (2001) 547**
2) *** Improved (based on SU(3) mB chiral Lagrangian): D. Cabrera, L. Tolos, J. Aichelin, E.B., PRC90 (2014) 055207**

The coupled-channel G-matrix approach

Solution of the Bethe-Salpeter equation in coupled channels:

Medium:

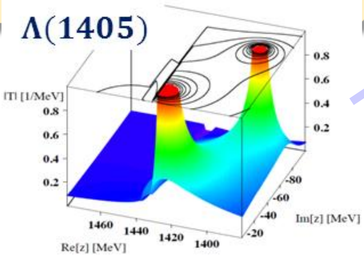


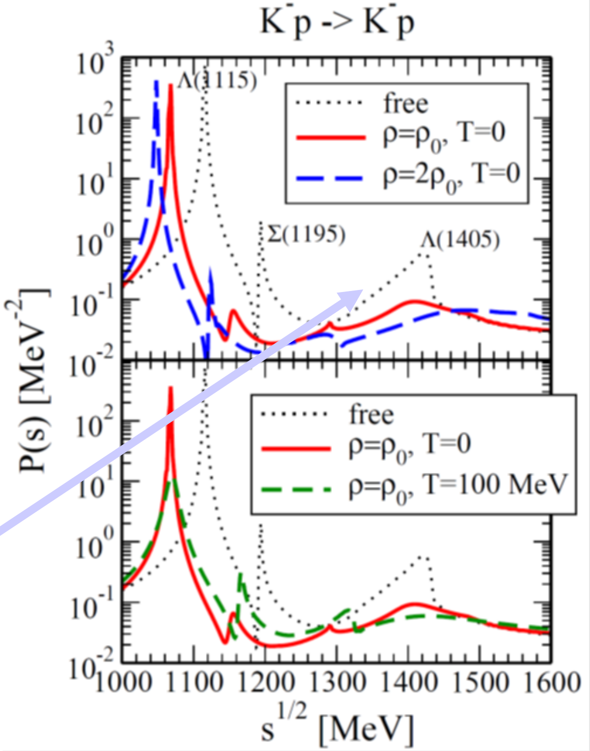
$P \propto |T|^2$

$$\mathcal{T}_{ij}(\rho,T) = V_{ij} + V_{il}\, G_l(\rho,T)\, \mathcal{T}_{lj}(\rho,T)$$

Coupled-channels [full $SU(3)$ basis, isospin $I = 0,1$]

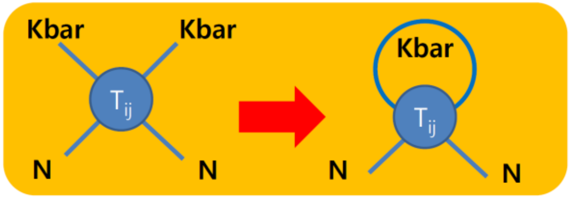
- $S=-1$: K^-p, $\bar{K}^0 n$, $\pi^0\Lambda$, $\pi^0\Sigma^0$, $\eta\Lambda$, $\eta\Sigma^0$, $\pi^+\Sigma^-$, $\pi^-\Sigma^+$, $K^+\Xi^-$, $K^0\Xi^0$
  K^-n, $\pi^0\Sigma^-$, $\pi^-\Sigma^0$, $\pi^-\Lambda$, $\eta\Sigma^-$, $K^0\Xi^-$
- $S=+1$: K^+p; K^+n, K^0p

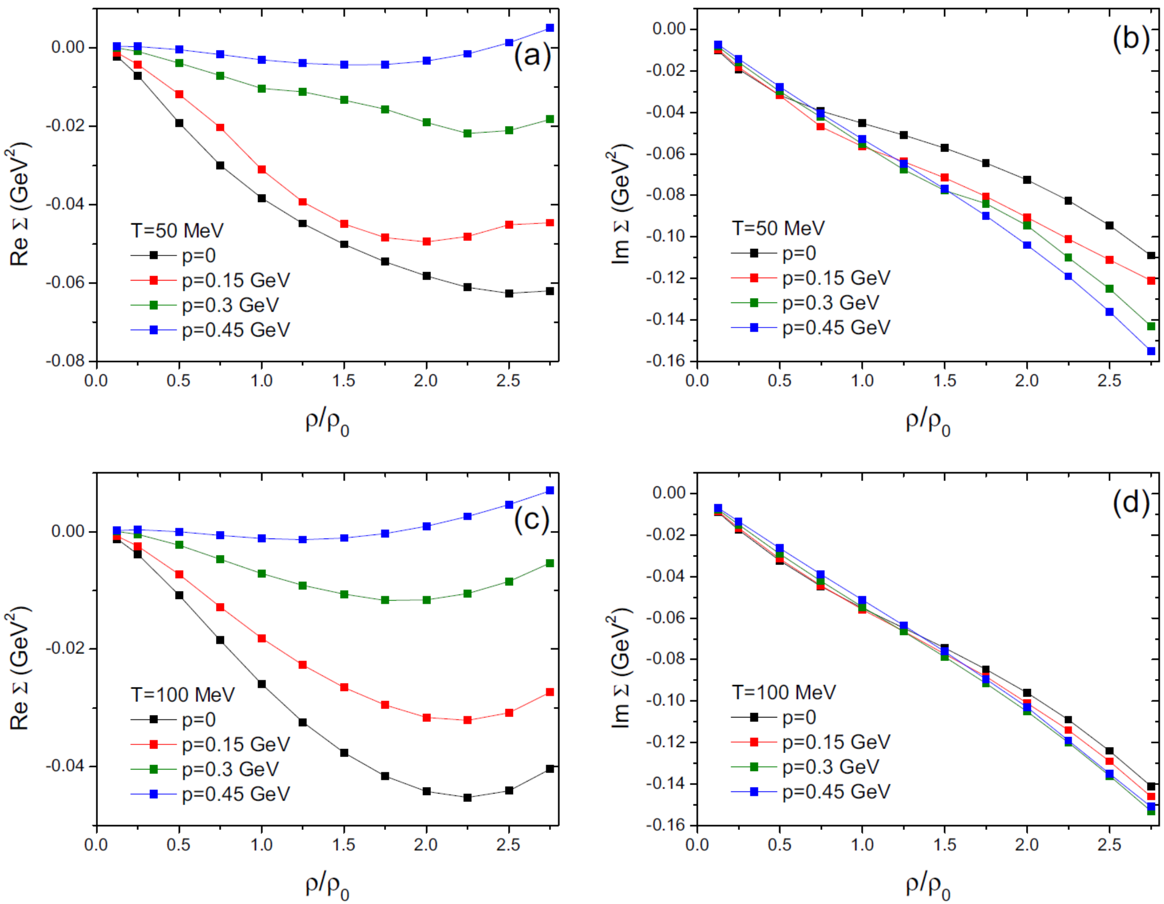




D. Cabrera, L. Tolos, J. Aichelin, E.B., PRC90 (2014), 055207

The self-energy of Kbar (K^-, K0bar)





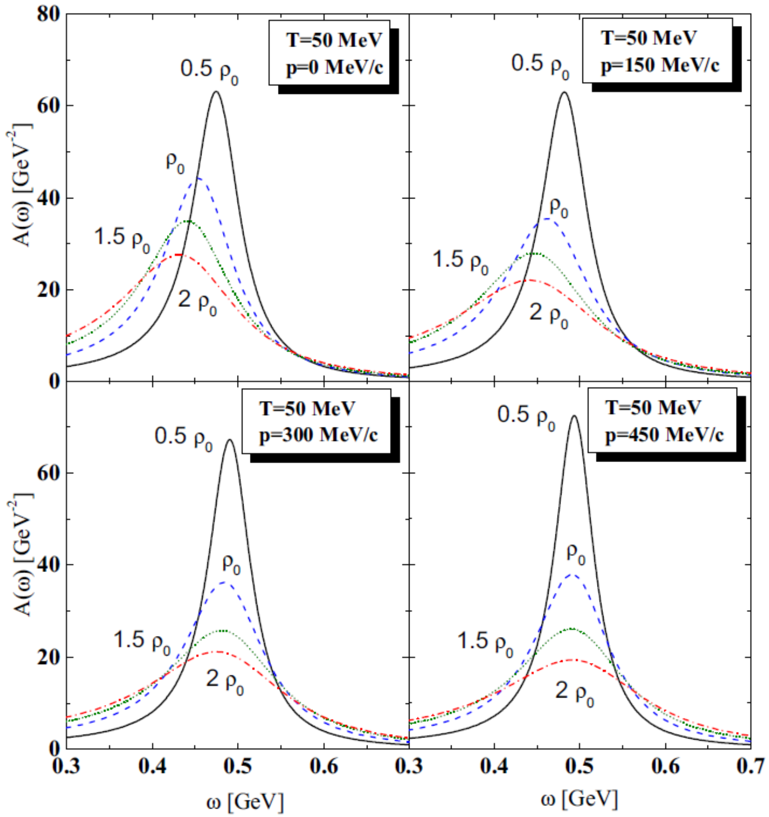
- Real & imaginary self-energies decrease with nuclear density for static antikaons (**p=0**) (black lines)
- Temperature effect is weak
- The **real part** of self- energy decreases with increasing antikaon momentum p
- The **imaginary part** of self-energy depends on p only weakly
- improved G-matrix (with *p*-wave in SU(3) chiral Lagrangian): potential (ReΣ) is more shallow at finite p

T. Song et al., PRC 103, 044901 (2021)

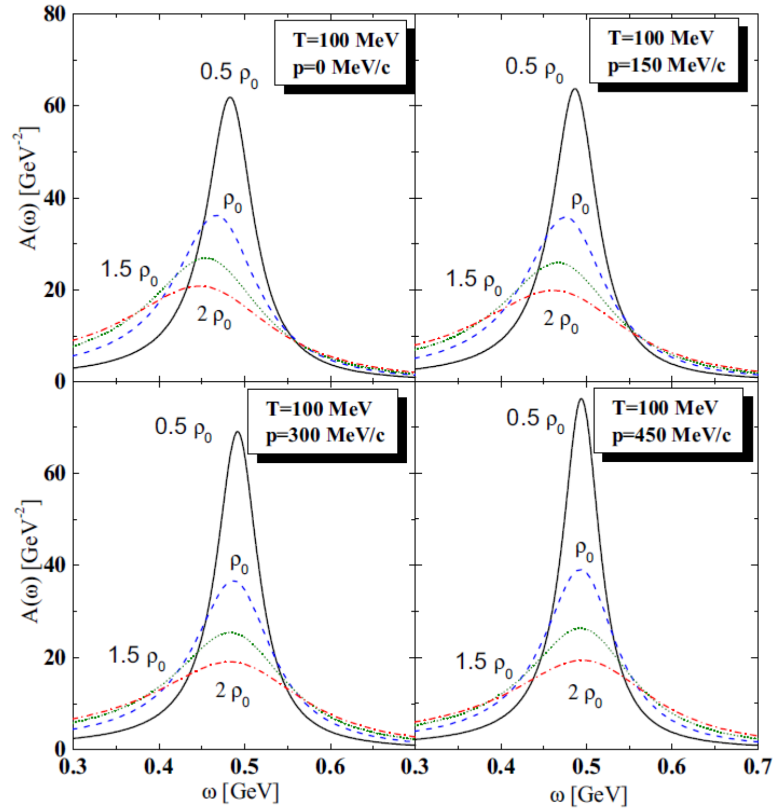
Spectral function of antikaon

$$A_{\bar{K}}(\omega, \mathbf{k}) = \frac{-2\,\mathrm{Im}\,\Sigma_{\bar{K}}}{\left(\omega^2 - \mathbf{k}^2 - m_{\bar{K}}^2 - \mathrm{Re}\,\Sigma_{\bar{K}}\right)^2 + (\mathrm{Im}\,\Sigma_{\bar{K}})^2}$$

T=50 MeV



T=100 MeV



- **Broadening of spectral function with density**
- **Relatively weak T and p dependence of ImΣ**

T. Song et al., PRC 103, 044901 (2021)

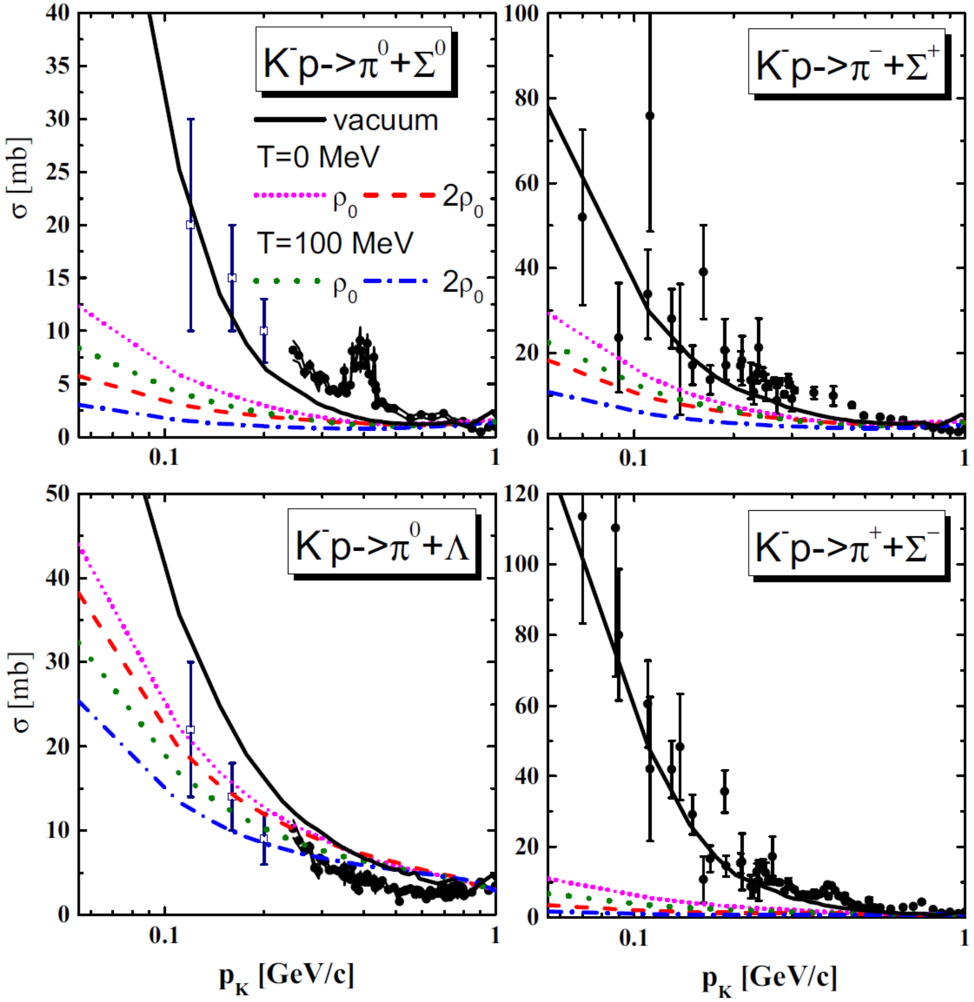
In-medium interaction cross sections

In-medium interaction cross sections:

$$\frac{d\sigma_{ij}}{d\Omega}(\sqrt{s}) = \frac{1}{16\pi^2}\frac{M_i M_j}{s}\frac{q_j}{q_i} \times\left\{\left|T^s_{ij} + \left(2T^p_{ij+} + T^p_{ij-}\right)\cos\theta\right|^2 + \left|T^p_{ij+} - T^p_{ij-}\right|^2 \sin^2\theta\right\},$$

in-medium transition amplitudes

- **Free cross sections (T=0, ρ=0) are comparable with the experimental data from elementary collisions**
- **Cross sections decrease with increasing nuclear density, partly due to Paul blocking**



T. Song et al., PRC 103, 044901 (2021)

In-medium K,Kbar production cross sections

- **Kaon production**

  K production is suppressed: $\Delta m_K>0$ – shift of threshold to larger $s^{1/2}$:

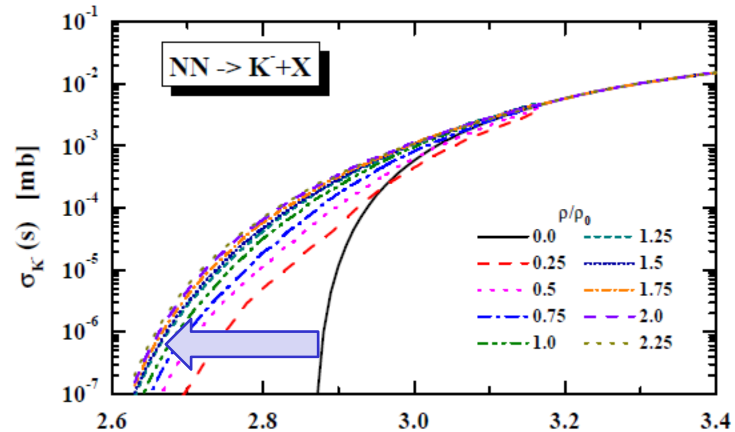
$$\sigma_{NN\to NYK}(\sqrt{s}) \to \sigma_{NN\to NYK^*}(\sqrt{s}-\Delta m_K) \quad \text{where } \Delta m_K = m_K^* - m_K$$

- **Antikaon production**

  $\bar{K}$ production is enhanced:

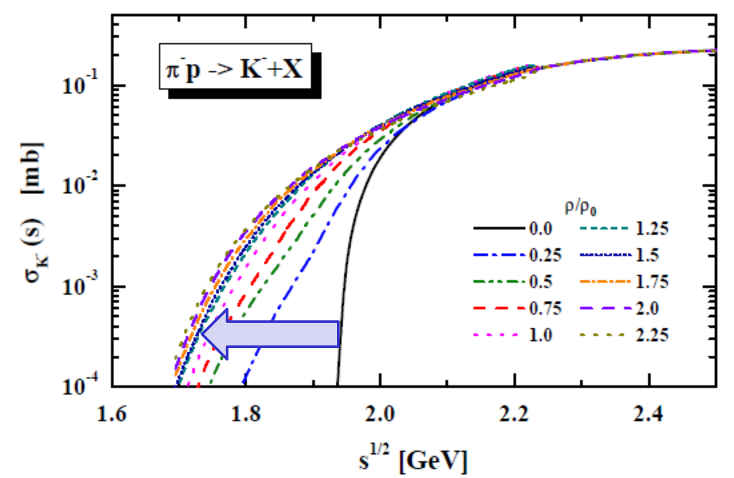
  $\Delta m_K<0$ – shift of threshold to smaller $s^{1/2}$

$$\sigma_{\bar{K}}^*(\sqrt{s}) = \int_0^{(\sqrt{s}-m_4)^2} \frac{dm^2}{2\pi} A(m^2)\, \sigma_{\bar{K}}(\sqrt{s}-\Delta m_{\bar{K}})$$



- **Production of antikaon and kaon pairs (e.g.: N π→N K Kbar, Φ→K Kbar, …) :**

$$\sigma_{K\bar{K}}^*(\sqrt{s}) = \int_0^{(\sqrt{s}-m_4)^2} \frac{dm^2}{2\pi} A(m^2)\sigma_{K\bar{K}}(\sqrt{s}-\Delta m_K - \Delta m_{\bar{K}})$$



T. Song et al., PRC 103, 044901 (2021)

Dynamical description of in-medium effects:

Off-shell transport theory for strongly interacting systems

Transport description of strongly interacting systems

Many-body theory :
Strong interactions ➔ large width = short life-time
➔ broad spectral functions ➔ quantum objects

- **How to describe the dynamics of broad strongly interacting quantum states in transport theory?**

Mandatory for the description of strongly-interacting matter and in-medium effects!

❑ **semi-classical BUU**

⇓

First-order gradient expansion of quantum Kadanoff-Baym equations for Green function

❑ **generalized transport equations = off-shell transport approach!**

(Anti)kaon off-shell propagation

On-shell propagation for kaon (normal BUU type)

$$\frac{dr_i}{dt} = \frac{\partial H}{\partial p_i} = \frac{p_i}{E},$$

$$\frac{dp_i}{dt} = -\frac{\partial H}{\partial r_i} = -\nabla V_K(r)$$

where $i = 1, 2, 3.$

Off-shell propagation for antikaon within generalized Cassing-Juchem EoM based on Kadanoff-Baym Equations

$$\frac{dr_i}{dt} = \frac{1}{1-C}\frac{1}{2E}\left[2p_i + \nabla_p \mathrm{Re}\,\Sigma + \frac{M^2 - M_0^2}{\mathrm{Im}\,\Sigma}\nabla_p \mathrm{Im}\,\Sigma\right]$$

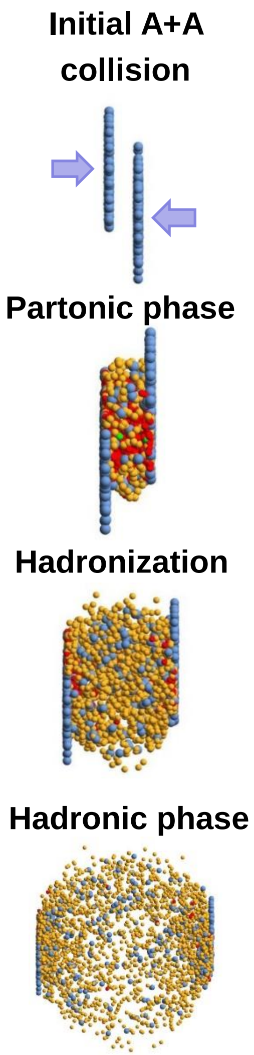
$$\frac{dp_i}{dt} = \frac{-1}{1-C}\frac{1}{2E}\left[\nabla_r \mathrm{Re}\,\Sigma + \frac{M^2 - M_0^2}{\mathrm{Im}\,\Sigma}\nabla_r \mathrm{Im}\,\Sigma\right]$$

$$\frac{dE}{dt} = \frac{1}{1-C}\frac{1}{2E}\left[\partial_t \mathrm{Re}\,\Sigma + \frac{M^2 - M_0^2}{\mathrm{Im}\,\Sigma}\partial_t \mathrm{Im}\,\Sigma\right]$$

Equivalent in the limit $\mathrm{Im}\Sigma$, $\nabla p \mathrm{Re}\Sigma \rightarrow 0$

W. Cassing , S. Juchem, NPA 665 (2000) 377; 672 (2000) 417; 677 (2000) 445

Parton-Hadron-String-Dynamics (PHSD)



PHSD is a non-equilibrium microscopic transport approach for the description of strongly-interacting hadronic and partonic matter created in heavy-ion collisions

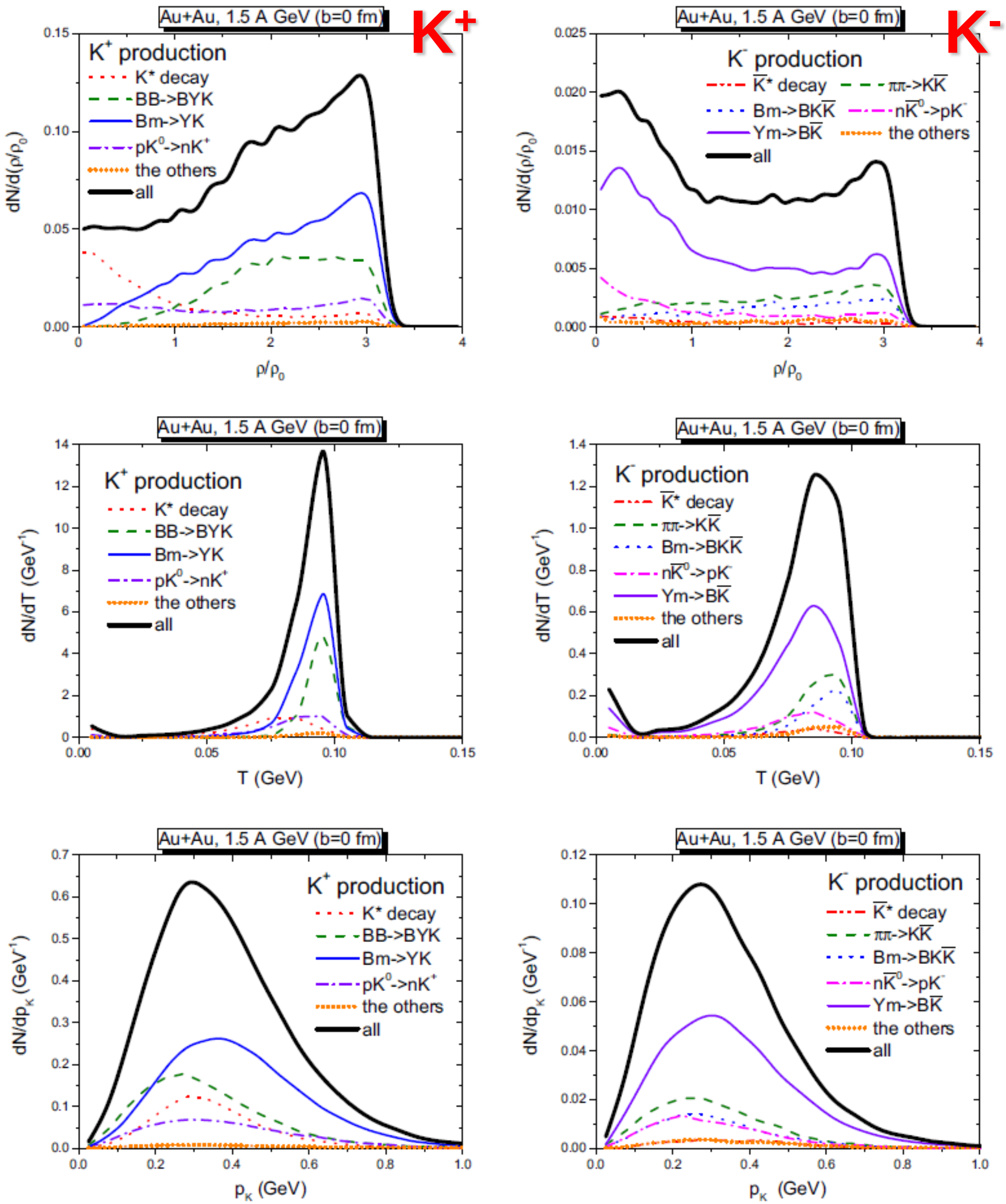
- **Dynamics:**
  based on the solution of generalized off-shell Cassing-Juchem transport equations derived from Kadanoff-Baym many-body theory

- **Generalized off-shell collision integral for *n* ←→ *m* reactions:**
  applied here for strangeness production:
  B+B↔B+Y+K,   B+m↔B+K+Kbar

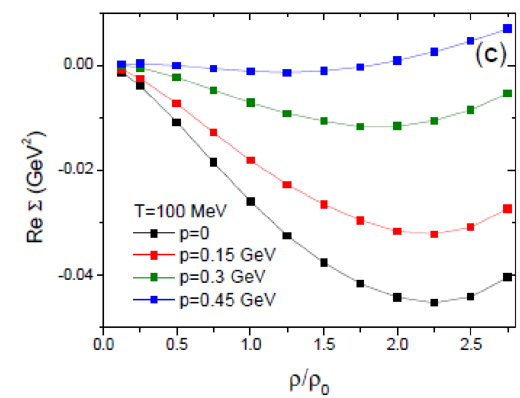
W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; W. Cassing, EPJ ST 168 (2009) 3

Dynamics of strangeness at SIS energies

ρ, T, p distributions of (anti)kaon production



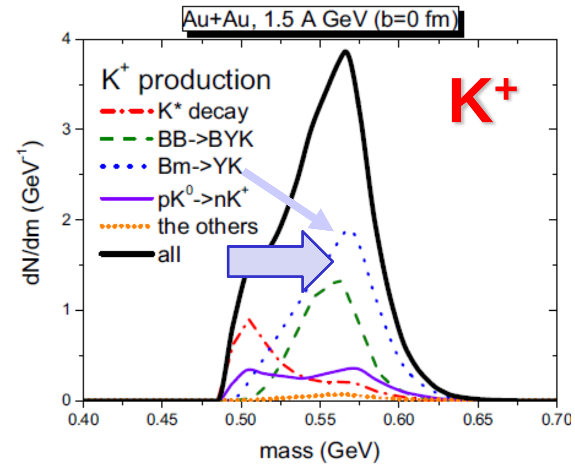
- **K** is produced at larger densities and higher temperatures than **Kbar**
- **Momenta of produced K and Kbar in nuclear matter are similarly peaked around p=200-400 MeV; at that momenta ReΣ is small**

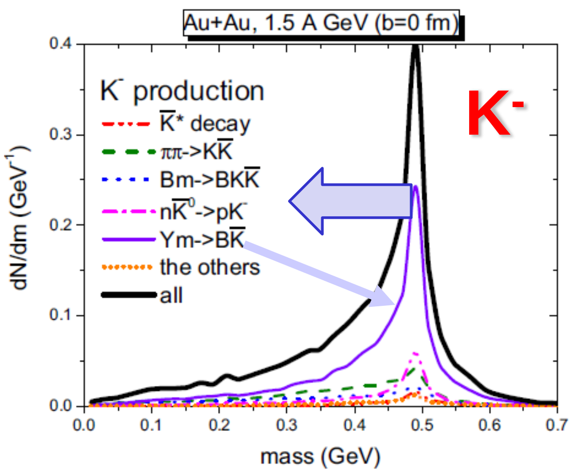


T. Song et al., PRC 103, 044901 (2021)

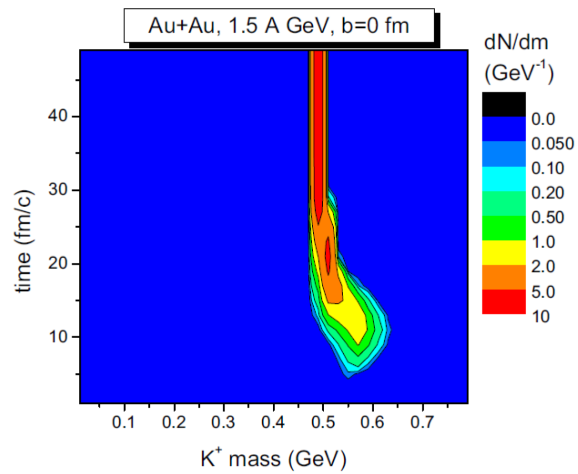
Time evolution of produced (anti)kaons

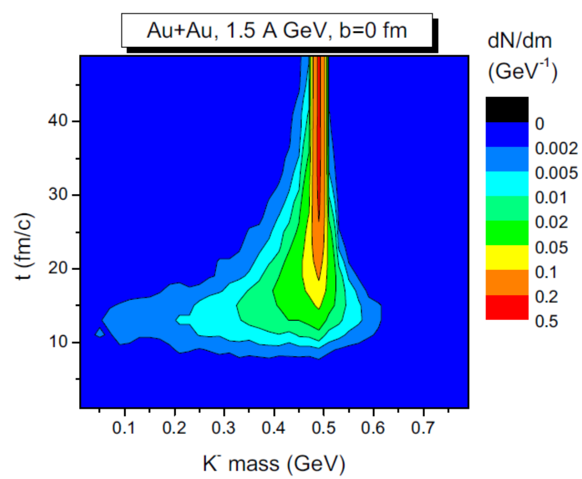
Mass distribution of K+, K- at the production points



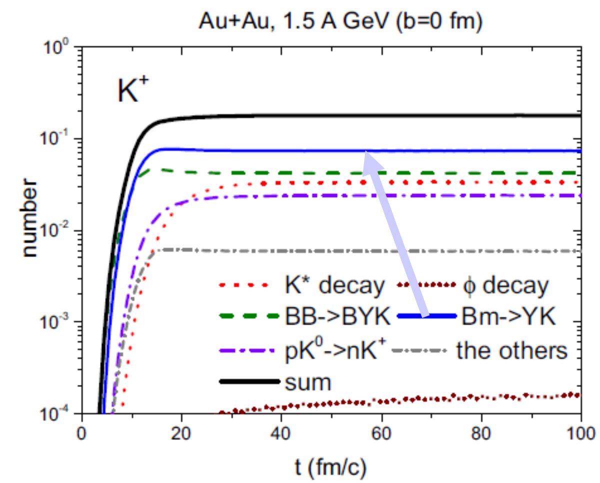


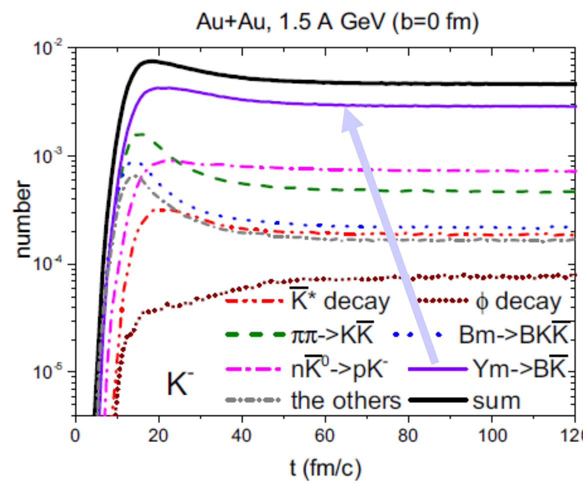
Time evolution of the K+, K- masses





Channel decomposition of the K+, K- production vs. time





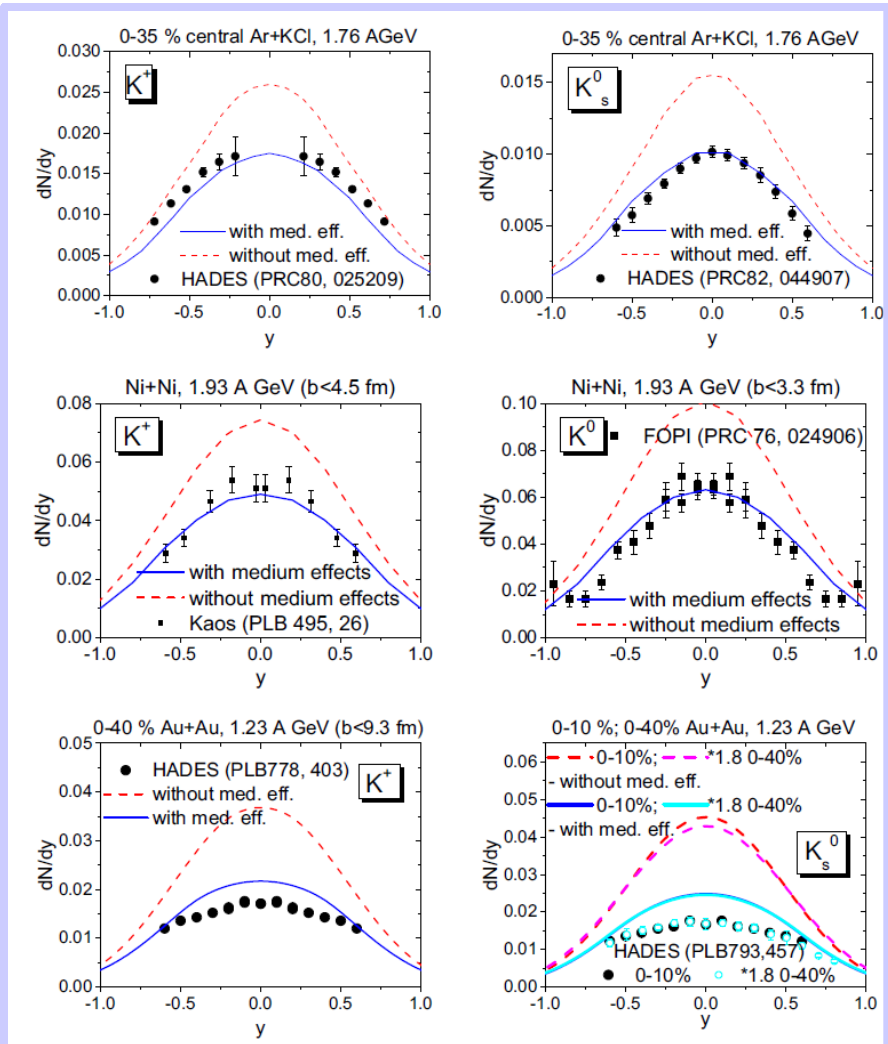
T. Song et al., PRC 103, 044901 (2021)

Comparison with experimental data at SIS energies

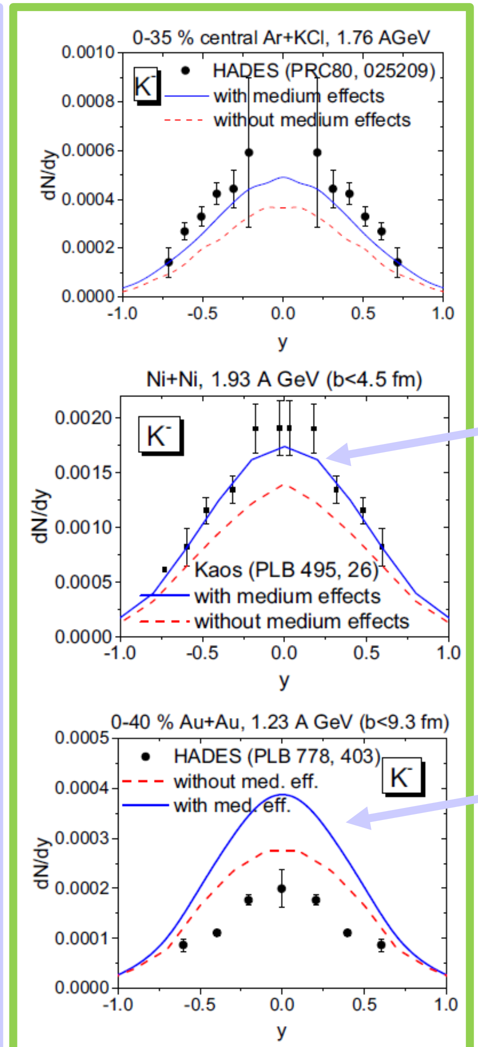
Rapidity distributions of (anti)kaons

T. Song et al., PRC 103, 044901 (2021)

K^+



K^-

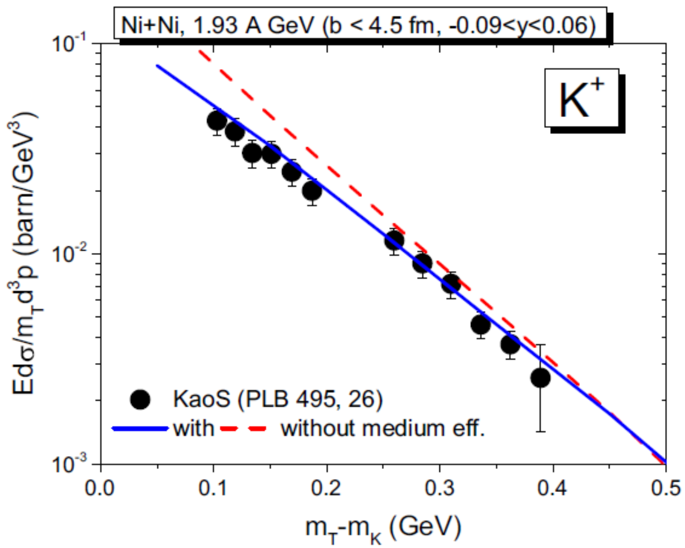


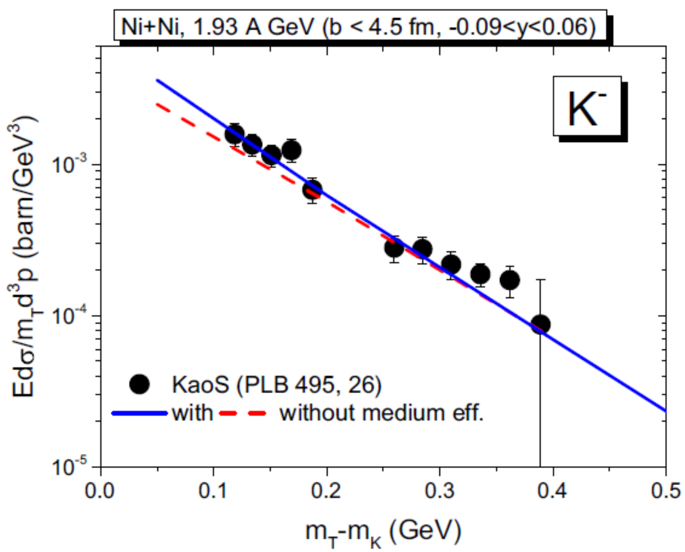
Good agreement with FOPI and KaoS data for K+ and K- for light and heavy A+A systems, as well as with HADES data for semi-heavy systems

Tension with HADES data for K- for Au+Au at 1.23 A GeV

- **Nuclear matter effects suppress kaon production**
- **Nuclear matter effects enhance antikaon production**

m_T spectra of (anti)kaons in central Ni+Ni collisions at 1.93 A GeV





In-medium effects:

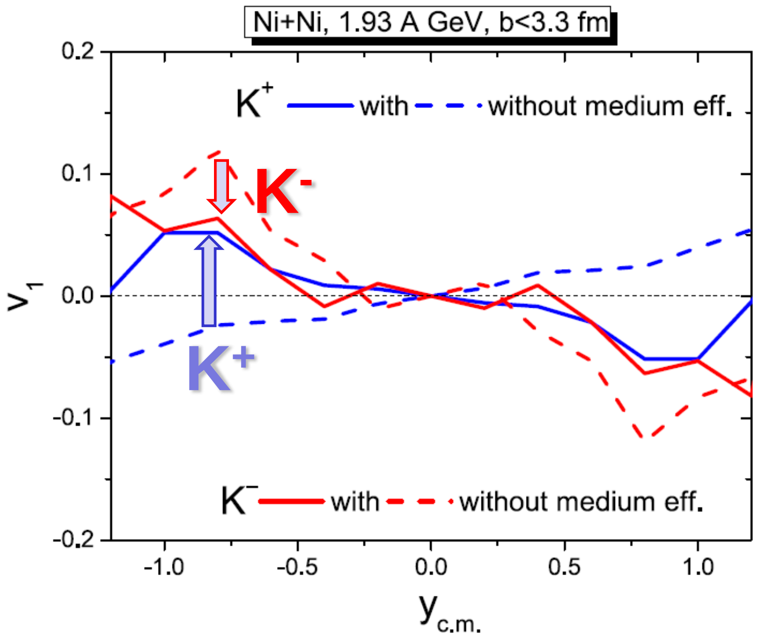
- **suppresses kaon production**
- **hardens kaon spectrum**
- **enhances antikaon production**
- **softens antikaon spectrum since for $M<M_0$, $\mathrm{Re}\Sigma \rightarrow 0$ and**

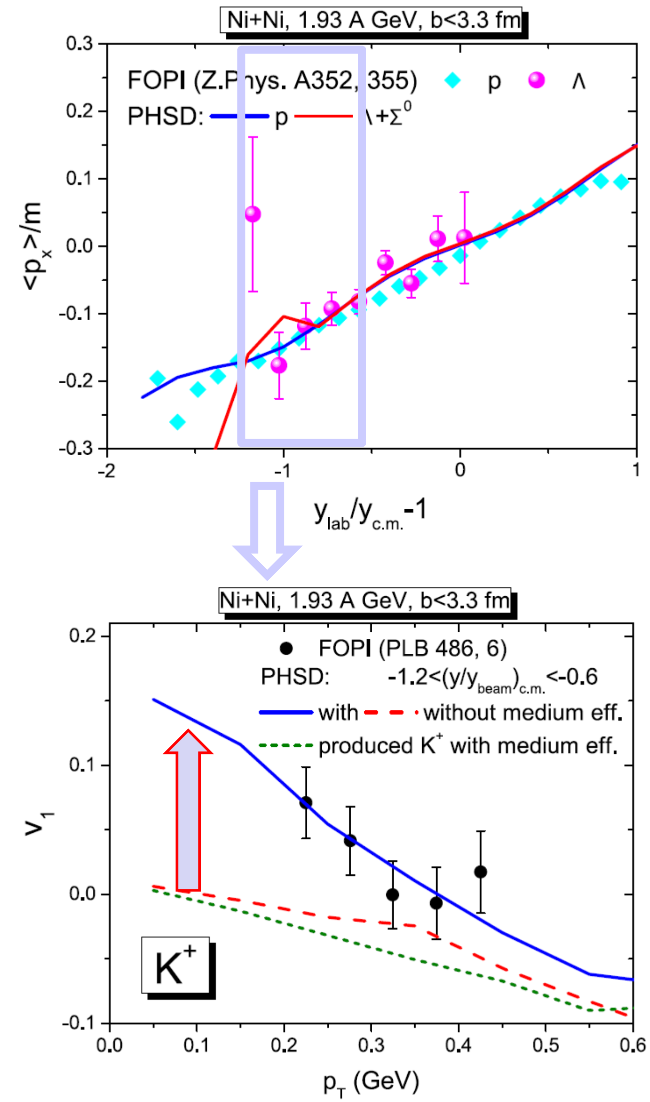
$$\frac{dp_i}{dt} \approx -\frac{1}{2E}\frac{M^2 - M_0^2}{\mathrm{Im}\Sigma}\nabla_r \mathrm{Im}\Sigma,$$

T. Song et al., PRC 103, 044901 (2021)

Directed flow (v_1)

$$\frac{dN(p_T,y)}{d\phi} = C[1 + 2v_1(p_T,y)\cos\phi + 2v_2(p_T,y)\cos(2\phi) + \cdots]$$





- v_1 of initial kaon follows that of nucleons while kaon is mostly produced by NN scattering
- repulsive force pushes v_1 of kaons upward
- attractive force pulls down v_1 of antikaon

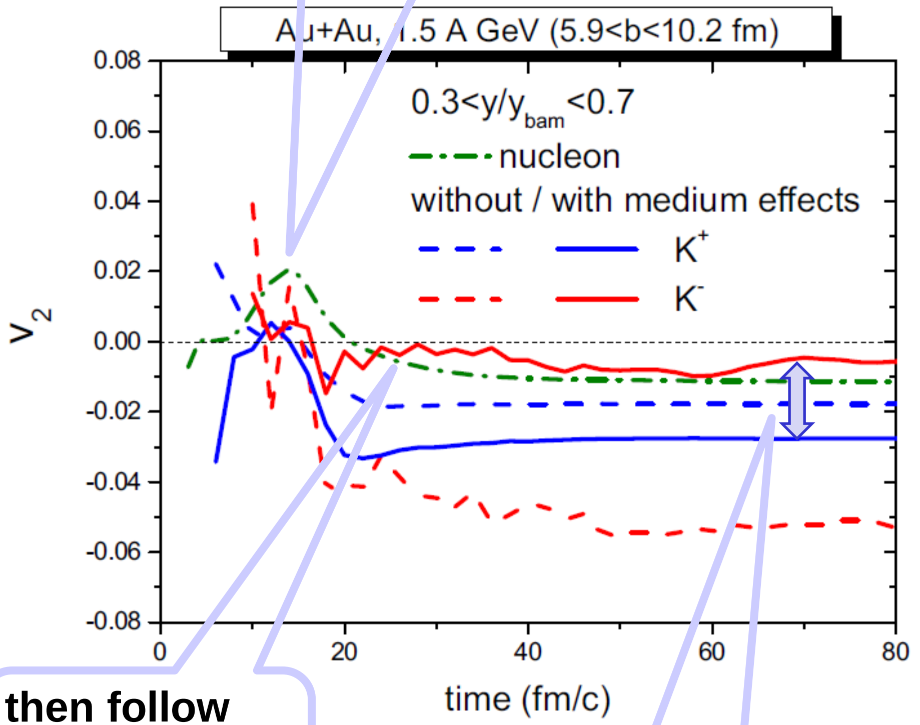
T. Song et al., PRC 103, 044901 (2021)

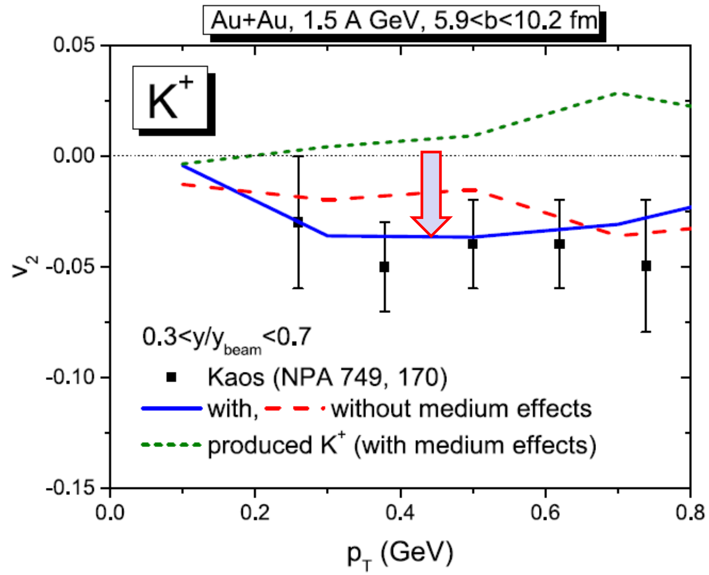
Elliptic flow (v_2)

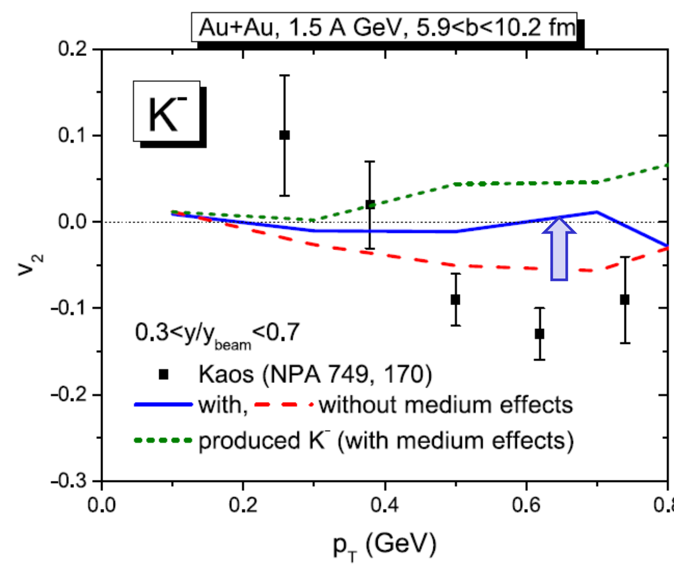
Most of (anti)kaons are produced when v_2 of nucleons >0

then follow negative v_2 of nucleons

In-medium effects split v_2 of K+, K-

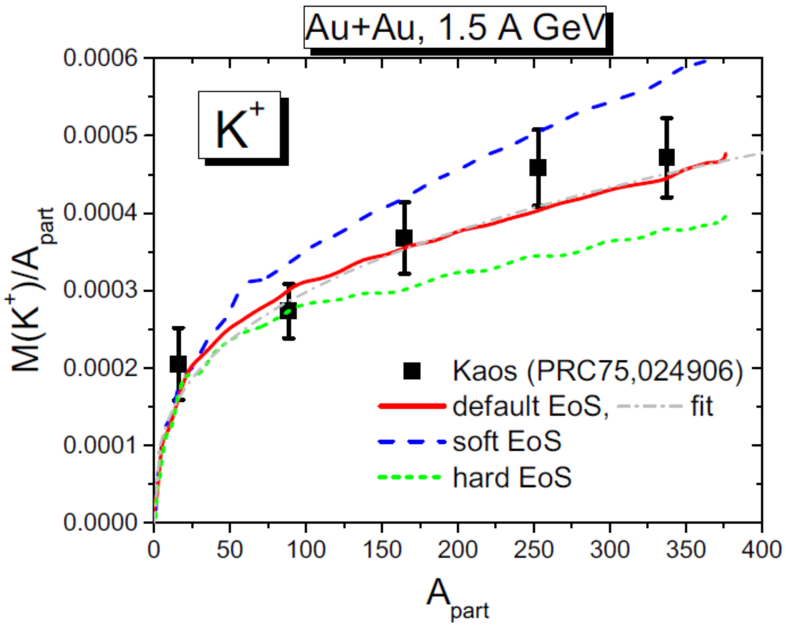


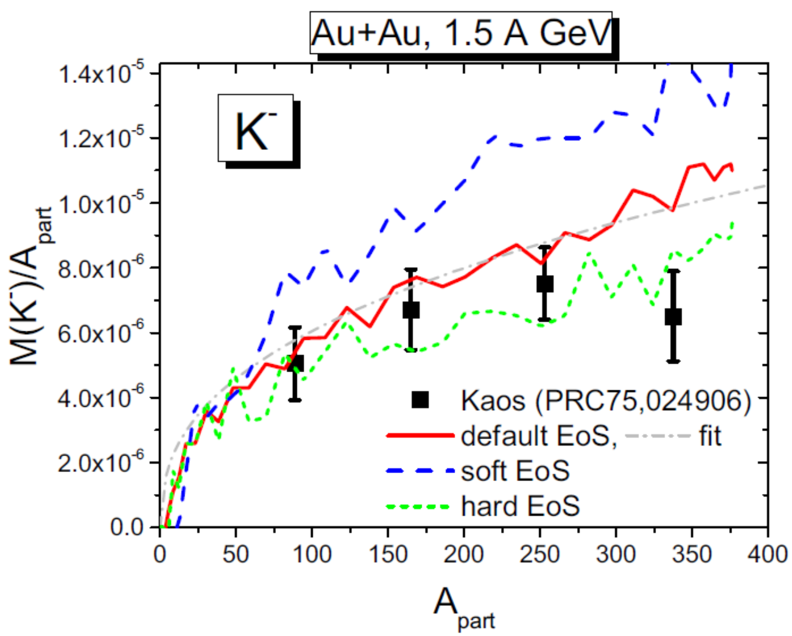




T. Song et al., PRC 103, 044901 (2021)

Equation of State (EoS) of nuclear matter





Skyrme potential

$$U(\rho) = a\left(\frac{\rho}{\rho_0}\right) + b\left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

where $a = -153$ MeV, $b = 98.8$ MeV, $\gamma = 1.63$.

Compression modulus K :

$$K = -V\frac{dP}{dV} = 9\rho^2 \frac{\partial^2 (E/A)}{\partial \rho^2}\Bigg|_{\rho_0}$$

Hard EoS: K=380 MeV
→ hard to be compressed,
less NN collisions to produce (anti)kaons

Default EoS: K=300 MeV

Soft EoS: K= 210 MeV
→ easy to be compressed,
more NN collisions to produce (anti)kaons

T. Song et al., PRC 103, 044901 (2021)

Summary

Strangeness production in heavy-ion collisions at (sub-)threshold energies is investigated within the Parton-Hadron-String Dynamics (PHSD) transport approach with off-shell propagation based on Kadanoff-Baym equations and detailed balance for 2↔3 interactions

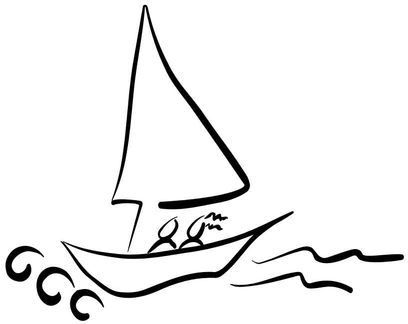
In-medium effects are realized by a G-matrix approach for antikaons and by a linear repulsive nuclear potential for kaons

T. Song et al., PRC 103, 044901 (2021)

Findings:

- The repulsive kaon nuclear potential increases the threshold energy for kaon production → suppression of kaon production, hardening of m_T spectra
- The broadening of Kbar spectral function in a medium decreases the threshold energy for antikaon production → enhancement of Kbar production, softening of m_T spectra
- Modification of v_1, v_2 of (anti-)kaons due to the in-medium effects
- Selectivity to EoS: soft EoS enhances and hard EoS suppresses the production of (anti)kaons; moderate EoS (K=300 MeV) reproduces experimental data better within the PHSD
- … still tension in description of HADES data for Au+Au at 1.23 A GeV
  Further robust experimental data are needed (HADES, CBM, BMN,…)!

... not yet the end of the ‚strange' adventure in the medium !



Thank you for your attention!