In-medium effects in strangeness production in heavy-ion collisions around the threshold energy

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The 19th International Conference on Strangeness in Quark Matter

May 17-21, 2021, sponsored by Brookhaven National Laboratory, Upton, New York

SQM2021

1. Introduction

- The properties of (anti)kaon are modified in a nuclear matter:
- It is expected that kaon is repulsive and antikaon is attractive to the nuclear matter
- To deal with antikaon in nuclear matter, we use self-consistent unitarized coupled-channel model in dense and hot matter (or G-matrix approach) based on the SU(3) meson-baryon chiral Lagrangian

2. G-matrix approach for antikaon

The lowest-order SU(3) chiral Lagrangian

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

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

Spin ½+ SU(3) octet

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

SU(3) pseudo-scalar meson

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

D. Cabrera, et al. PRC 90, 055207 (2014),

Self-consistent unitarization

SU(3) Chiral Lagrangian

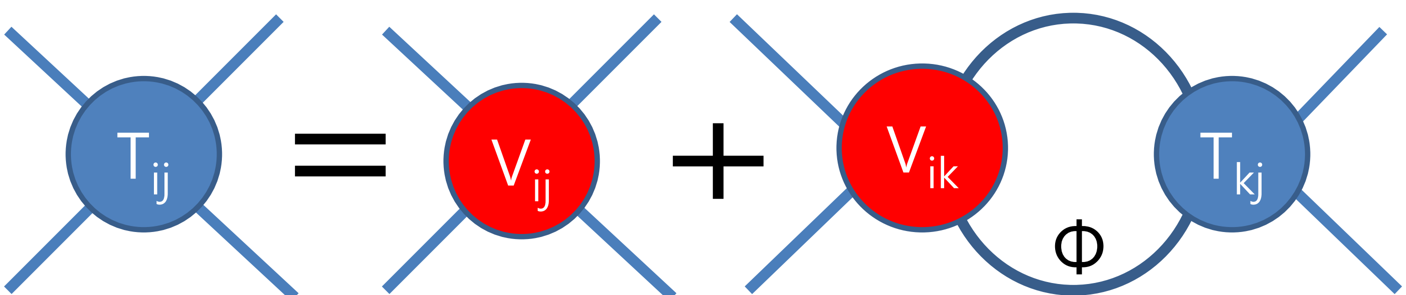
S-wave: $V^s_{ij} = -C_{ij}\frac{1}{4f^2}\bar{u}(p')\gamma^{\mu}u(p)(k_{\mu}+k'_{\mu}),$

P-wave: V_{ij}^{p}

D. Cabrera, et al. PRC 90, 055207 (2014),

For I_3=0, i, j=

$K^- p,\ \bar{K}^0 n,\ \pi^0\Lambda,\ \pi^0\Sigma^0,\ \eta\Lambda,\ \eta\Sigma^0,$
$\pi^+\Sigma^-,\ \pi^-\Sigma^+, K^+\Xi^-,\ K^0\Xi^0\ ,$



For I_3=-1, i, j=

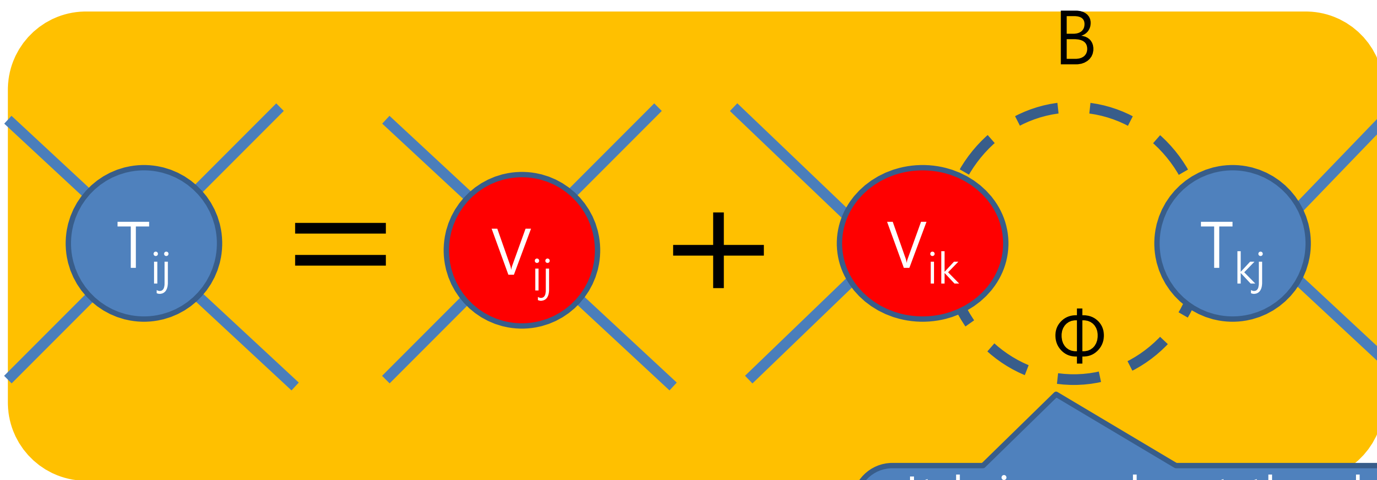
$K^- n,\ \pi^0\Sigma^-,\ \pi^-\Sigma^0,$
$\pi^-\Lambda,\ \eta\Sigma^-, K^0\Xi^-.$

$$T_{ij} = V_{ij} + \overline{V_{ik}G_{kk}T_{kj}},$$

Tolos et al., NPA 690 (2001) 547

Beyond one-boson exchange model

G-matrix in a hot & dense matter



It brings about the dressing of B and Φ propagators, and Pauli blocking to B; more advanced than T-matrix

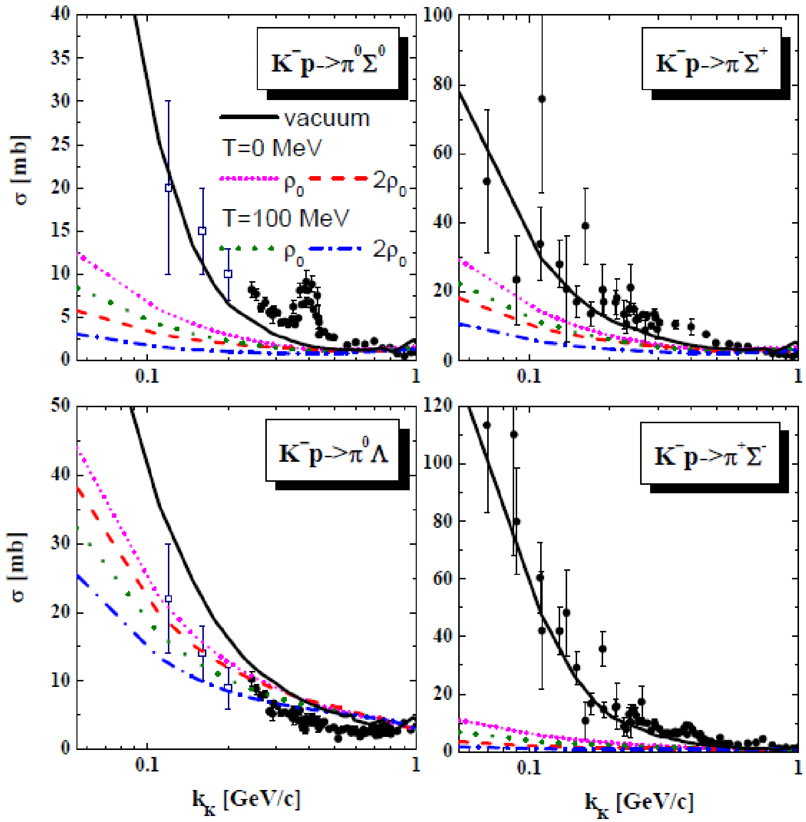
In vacuum

$$G_l(\sqrt{s}) = i\int \frac{d^4q}{(2\pi)^4}\frac{M_l}{E_l(\vec{P}-\vec{q})}\frac{1}{\sqrt{s}-q_0-E_l(\vec{P}-\vec{q})+i\varepsilon} \times \frac{1}{q_0^2-\vec{q}^{\,2}-m_l^2+i\varepsilon},$$

At finite T, μ

$$\mathcal{G}_{MB}(W_m,\vec{P};T) = -T\int\frac{d^3q}{(2\pi)^3}\sum_n \mathcal{D}_B(W_m-\omega_n,\vec{P}-\vec{q};T) \times \mathcal{D}_M(\omega_n,\vec{q};T),$$

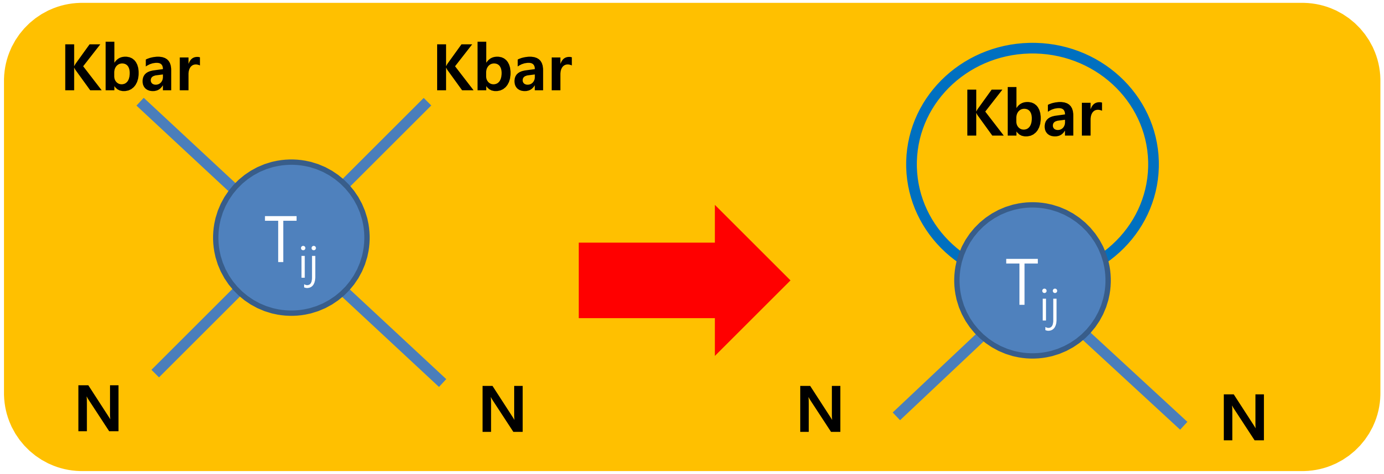
Comparison with Exp. data



D. Cabrera, et al. PRC 90, 055207 (2014),
T. Song et al. PRC 103, 044901 (2021)

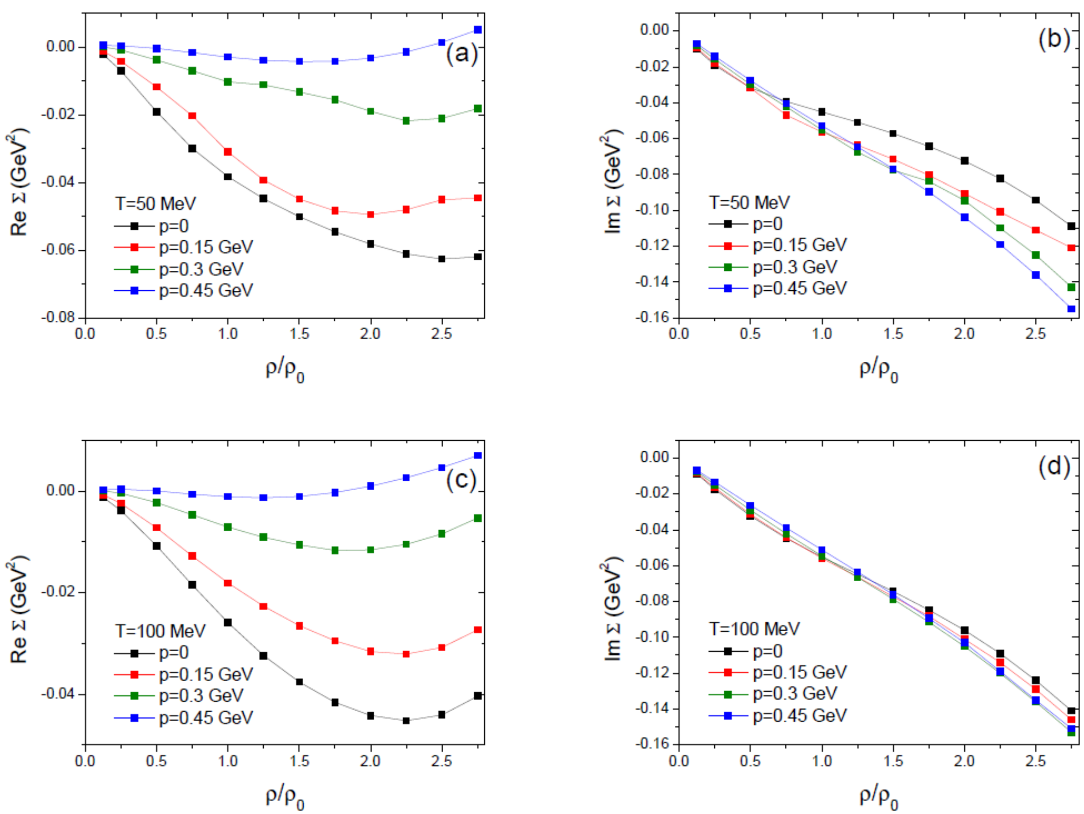
- Cross sections are comparable with the experimental data from elementary collisions
- Cross sections decrease with increasing nuclear density, partly from Paul blocking

The self energy of Kbar (K-, K0bar)



By connecting two Kbar legs,
the self energy of Kbar is obtained

Real & imaginary parts of self energy as a function of T, ρ and p



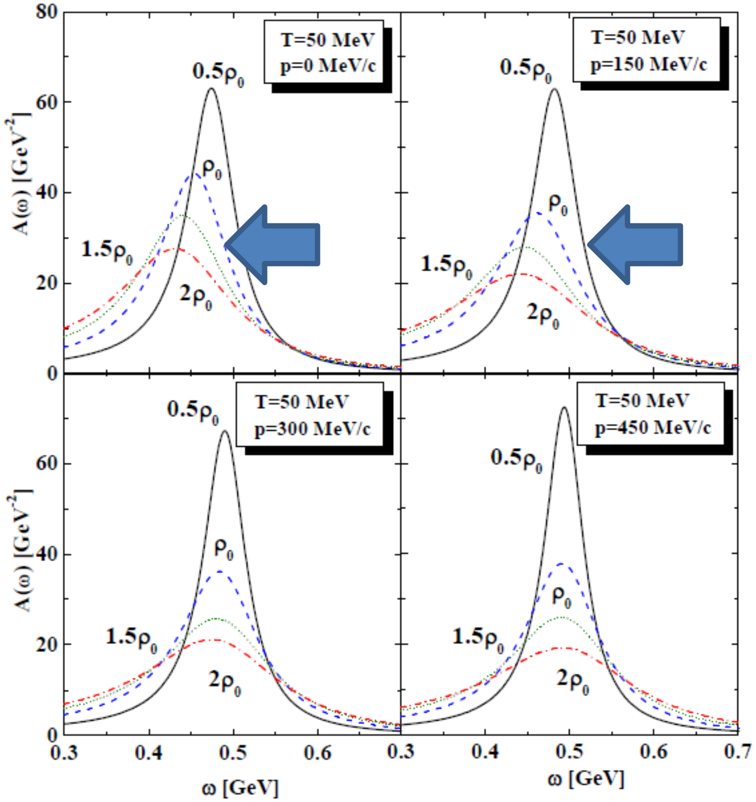
1. Real & imaginary self energies decrease with nuclear density for static antikaon (p=0, black lines)
2. Temperature effects are weak
3. As momentum of antikaon increases, the real part of self energy becomes small while the imaginary part of self energy little changes

D. Cabrera, et al. PRC 90, 055207 (2014)

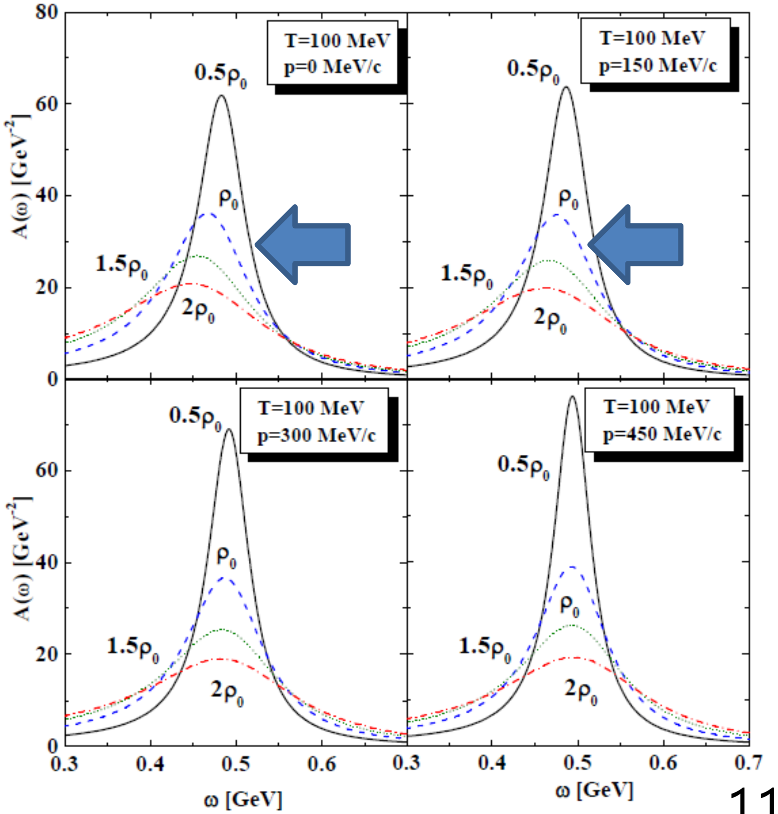
Spectral function of antikaon

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

T=50 MeV



T=100 MeV



Kaon in nuclear matter

- Repulsive potential in matter

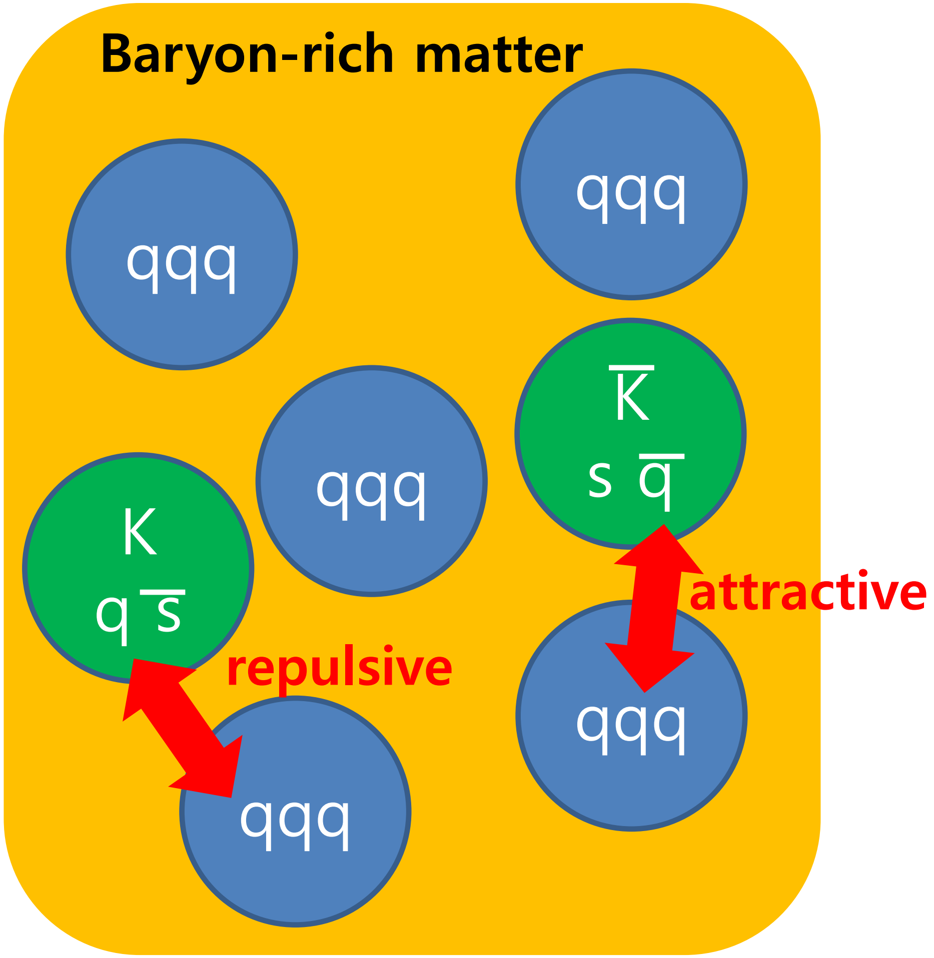
$$V_K = 25 \text{ MeV } (\rho/\rho_0),$$

is related to the increase of effective mass

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

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

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



Shifts of the threshold energy for (anti)kaon production

- **For kaon production** (K production is suppressed)

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

where $\Delta m_K = m_K^* - m_K$

- **For antikaon production** (Kbar production is enhanced)

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

- **For antikaon and kaon simultaneous production**

(for example, N π→N K Kbar, Φ→K Kbar, …)

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

(anti)kaon propagation

Off-shell propagation for antikaon from Kadanoff Baym Eq.

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

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

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

On-shell propagation for kaon (normal BUU type)

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

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

Equivalent in the limit Im∑, ∇_pRe∑ →0

W. Cassing et al., NPA 727, 59 (2003)

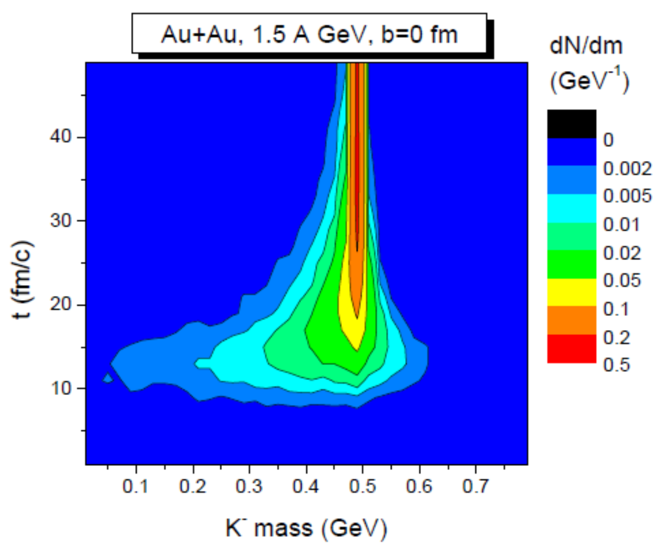
(anti)kaon propagation

Off-shell propagation for antikaon from Kadanoff Baym Eq.

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

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

$$\boxed{\frac{dM^2}{dt} = \frac{M^2 - M_0^2}{\mathrm{Im}\Sigma}\frac{d\mathrm{Im}\Sigma}{dt},}$$



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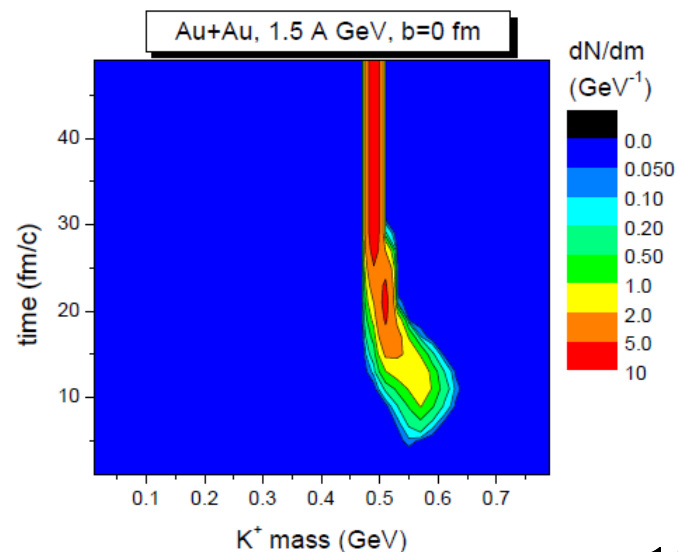
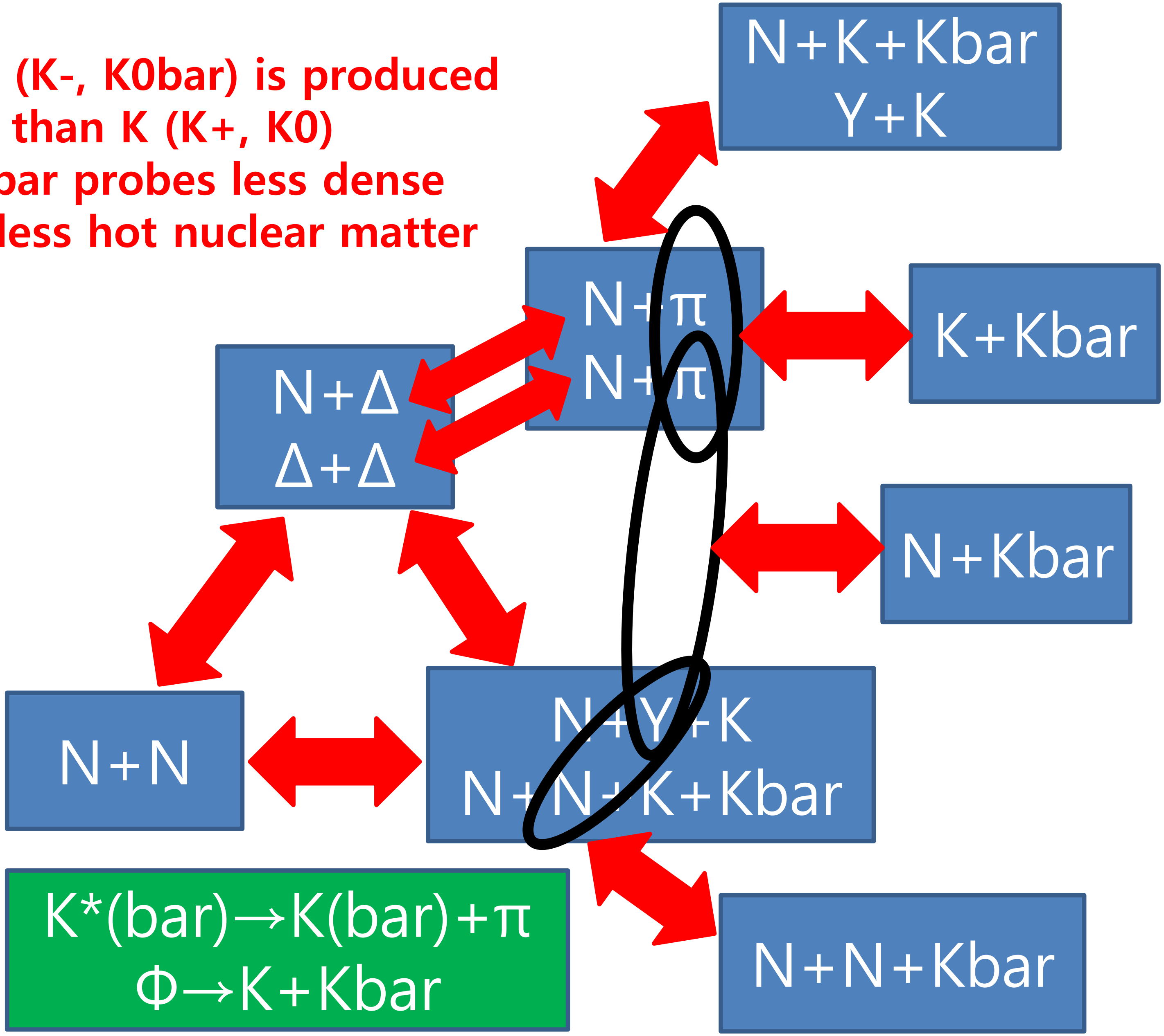


3. Strangeness production in heavy-ion collisions:

Parton-Hadron-String Dynamics (PHSD)

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

Kbar (K-, K0bar) is produced later than K (K+, K0)
→ Kbar probes less dense and less hot nuclear matter



Decays also contribute

Detailed balance 2↔3

for B+B↔B+Y+K, B+m↔B+K+Kbar

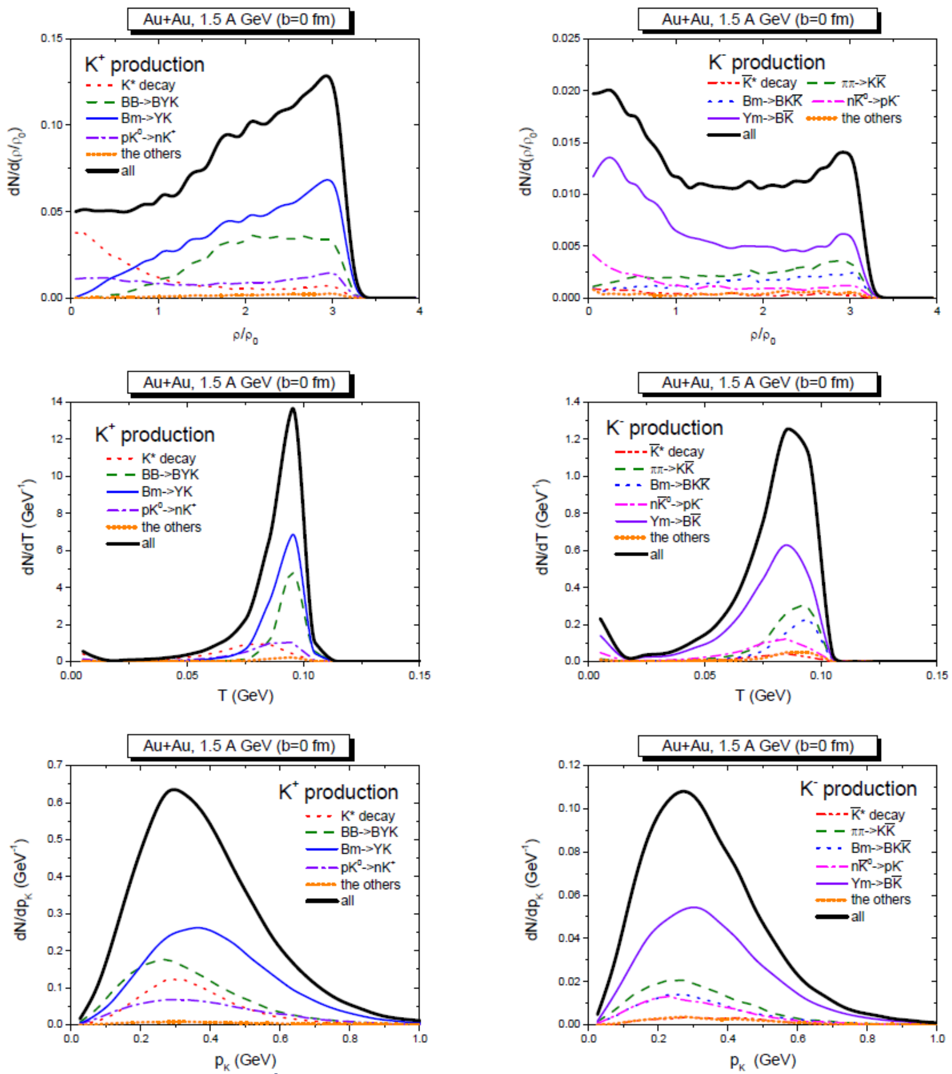
$$\sigma_{2\to 3} = \frac{1}{4E_1 E_2 v_{\rm rel}} \int \frac{d^3p_1'}{(2\pi)^3 2E_1'} \int \frac{d^3p_2'}{(2\pi)^3 2E_2'} \int \frac{d^3p_3'}{(2\pi)^3 2E_3'} \times \overline{|M|}^2 (2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_1' - p_2' - p_3'),$$

Same transition amplitude

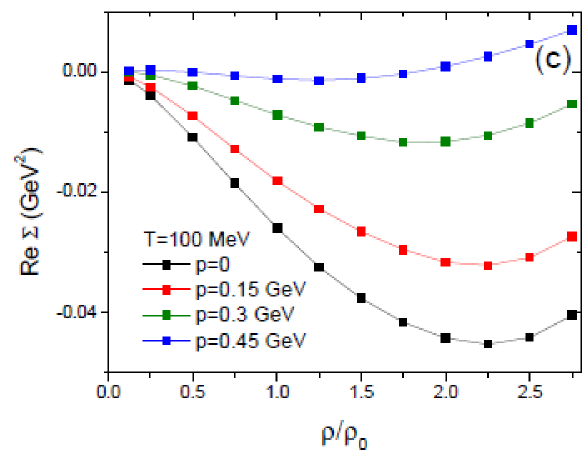
$$\frac{\Delta N^{3\to 2}}{\Delta t \Delta V} = \frac{1}{D_1' D_2' D_3'} \int \frac{d^3p_1}{(2\pi)^3 2E_1} \times \int \frac{d^3p_2}{(2\pi)^3 2E_2} \int \frac{d^3p_1'}{(2\pi)^3 2E_1'} f_1(p_1') \times \int \frac{d^3p_2'}{(2\pi)^3 2E_2'} f_2(p_2') \int \frac{d^3p_3'}{(2\pi)^3 2E_3'} f_3(p_3') \times |M|^2 (2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_1' - p_2' - p_3'),$$

W. Cassing, NPA 700 (2002) 618-646

ρ, T, p distributions of (anti)kaon production sites in central Au+Au, E=1.5 A GeV



- K is produced at larger densities and higher temperatures than Kbar
- Momenta of produced K and of Kbar in nuclear matter are similarly peaked around p=200-400 MeV, which makes Re∑ small



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

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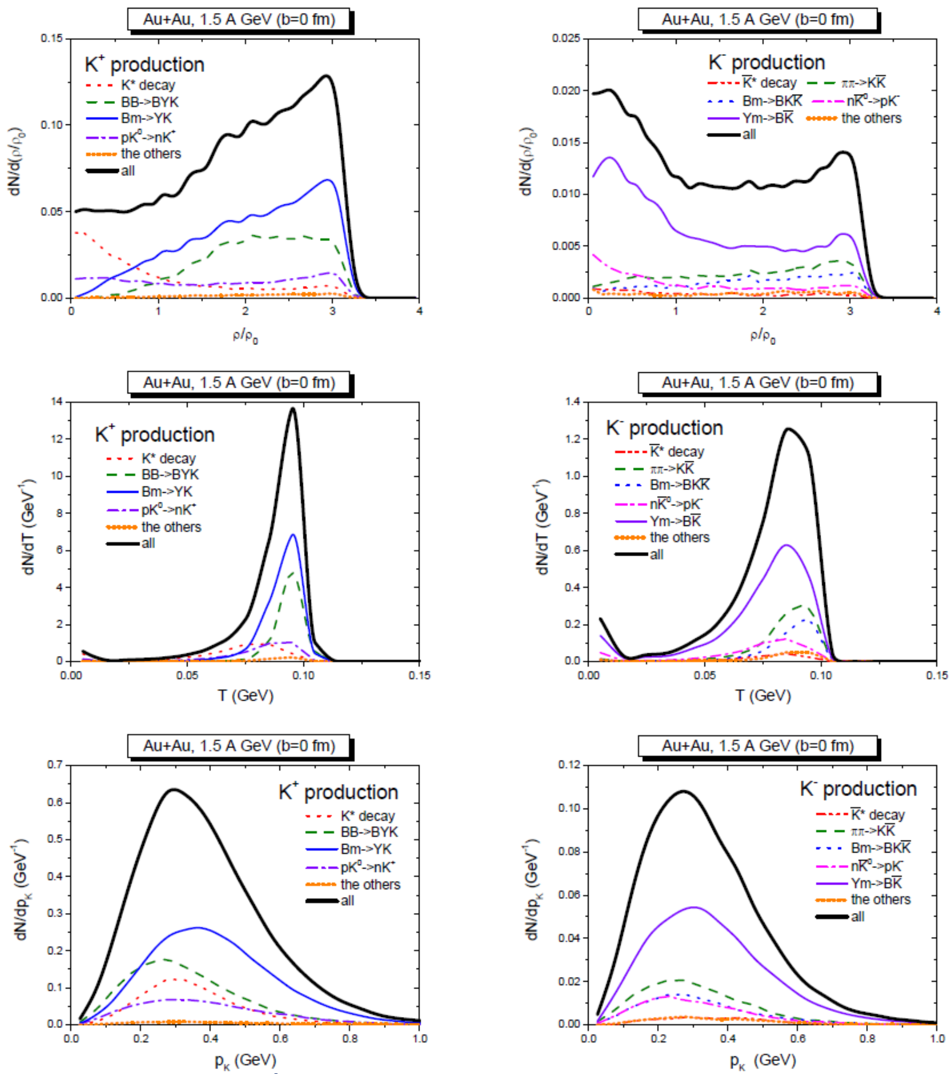

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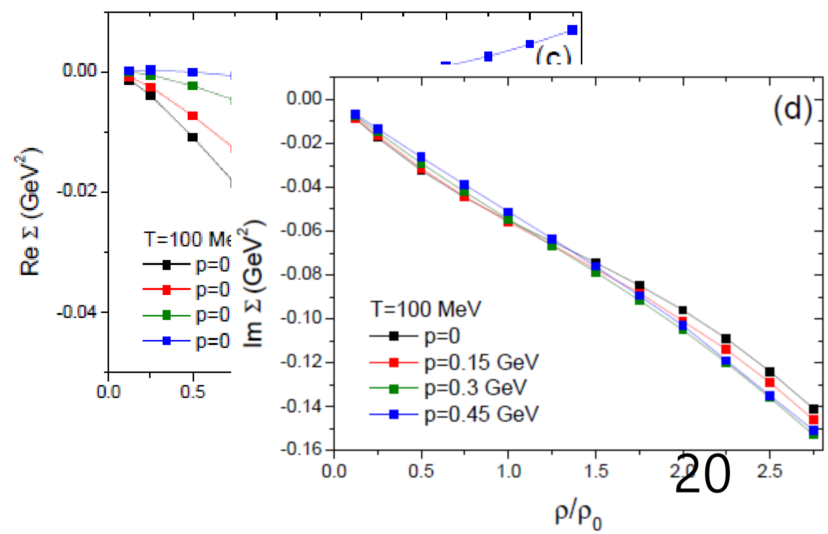
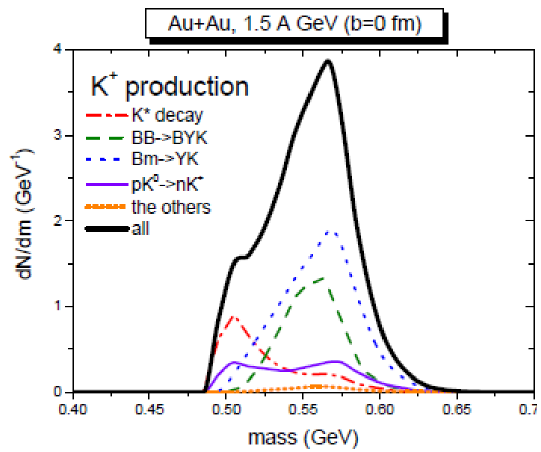
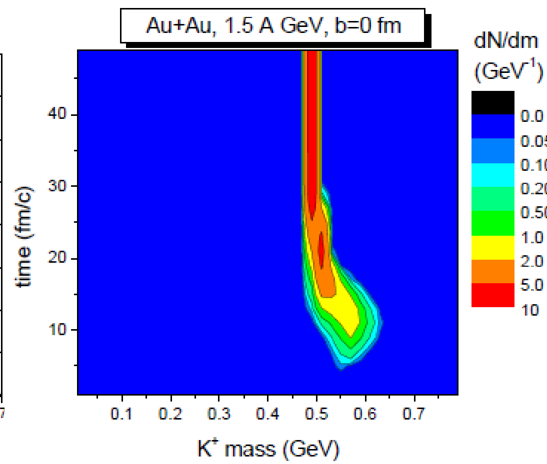
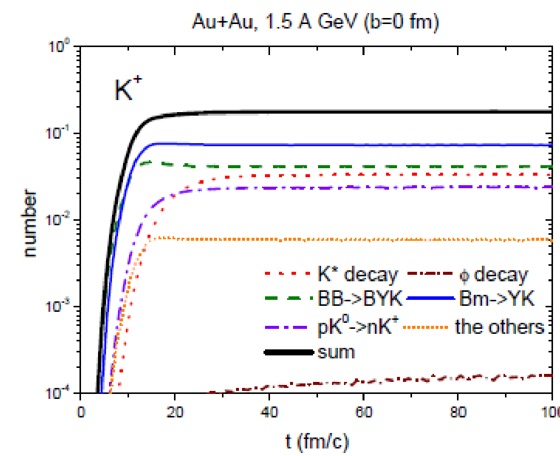


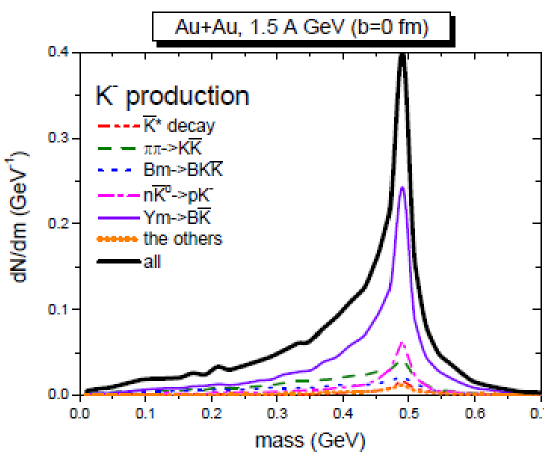
T. Song et al. PRC 103, 044901 (2021)

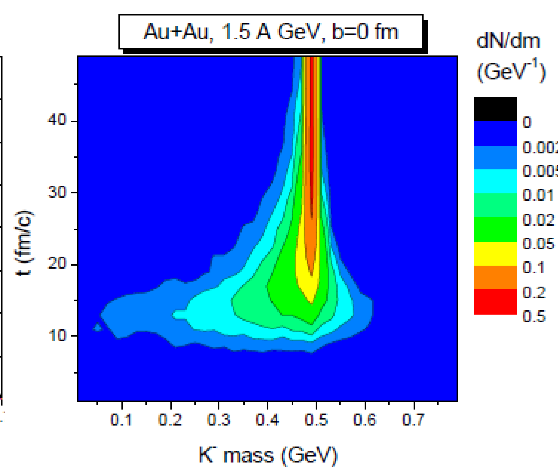
Time evolution of produced (anti)kaons in central Au+Au collisions at E=1.5 A GeV

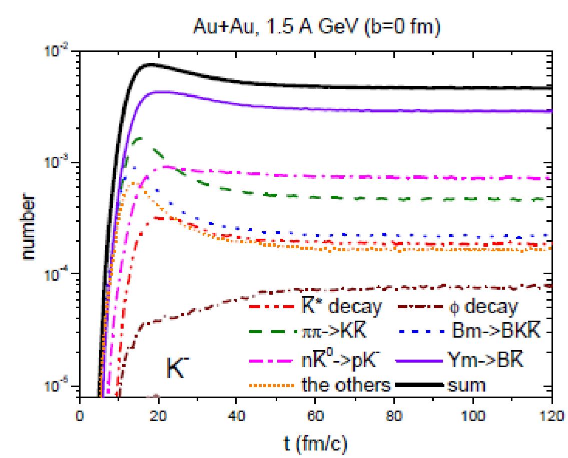










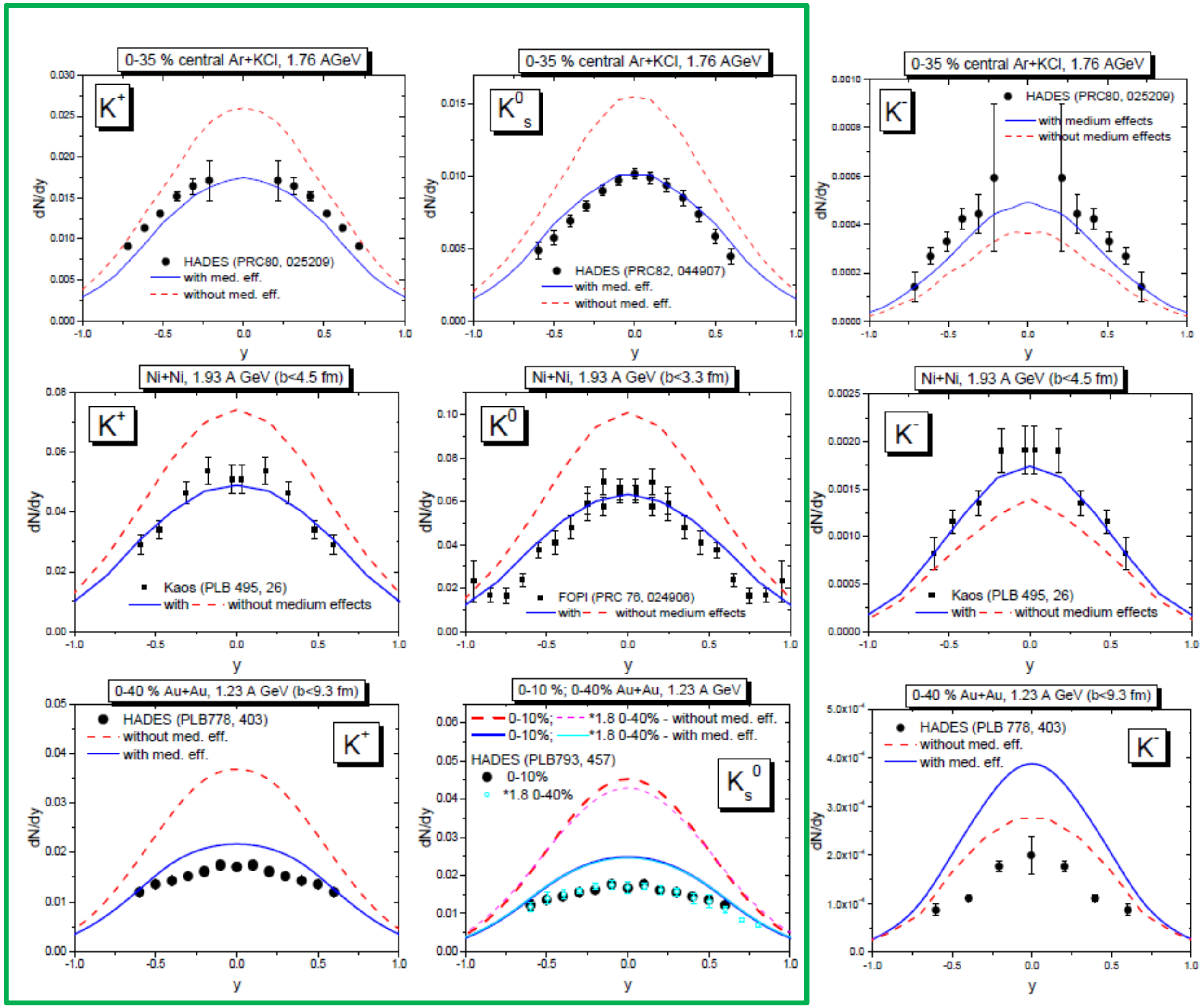


Initial mass distribution | Masses change with time | Channel decomposition

4. Comparison with experimental data

Rapidity distributions of (anti)kaons

Nuclear matter effects suppress kaon production



Nuclear matter effects enhance antikaon production

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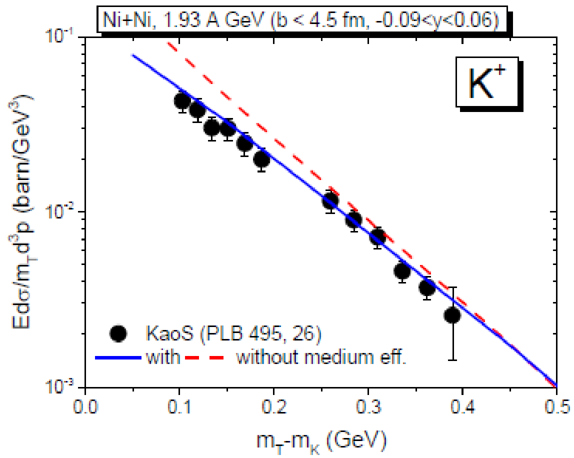
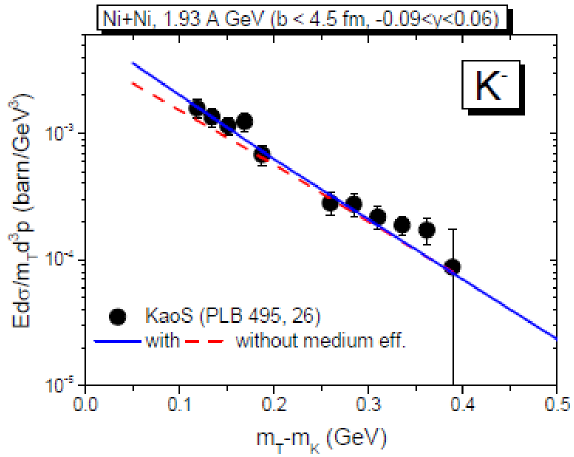
m_T spectra of (anti)kaons in central Ni+Ni collisions at E=1.93 A GeV





- Nuclear matter suppresses kaon production and hardens spectrum,
- while it enhances antikaon production and softens spectrum

- As for antikaon,

though $\mathrm{Re}\Sigma \approx 0$,pectrum softens for $M<M_0$

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

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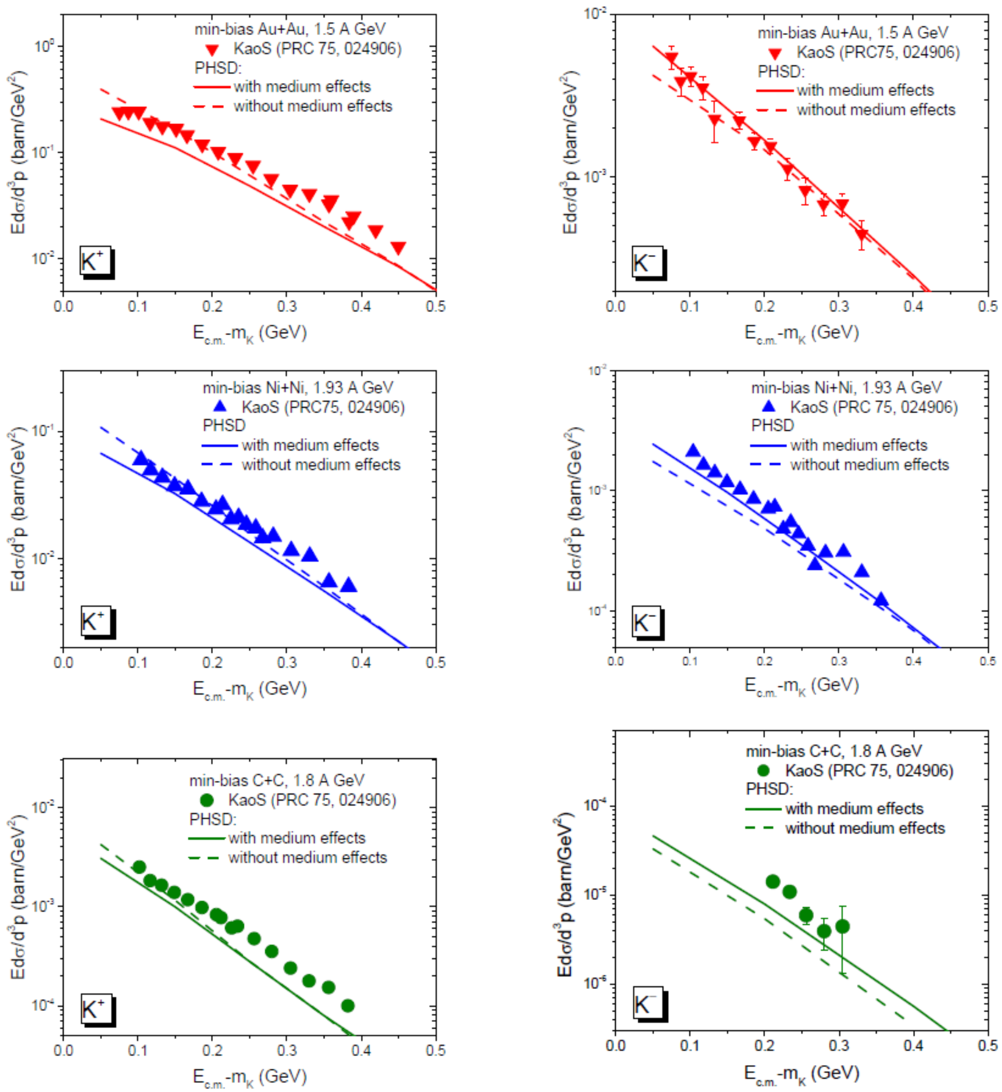
Cross sections for (anti)kaon production in min-bias heavy-ion collisions



$$\sigma_K^{AA} = N_K^{AA} \times \frac{\sigma_{inelastic}^{AA}}{N_{event}^{AA}}$$

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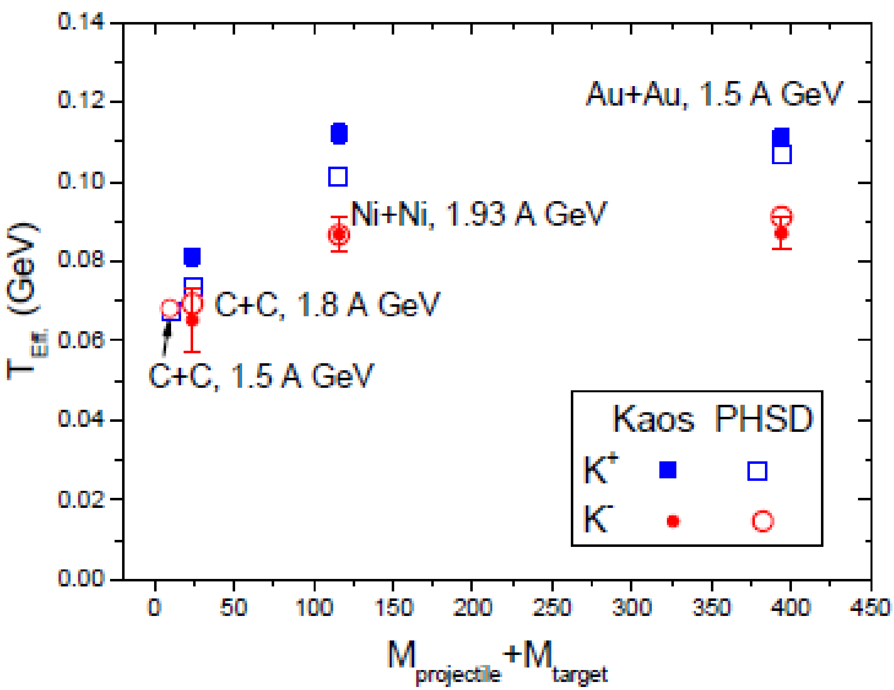
Effective temperature

$$E\frac{d\sigma}{d^3p} \sim E\exp\left(-\frac{E}{T}\right).$$



- Effective temperature increases with the size of colliding nuclei because of the stronger flow for larger system
- Nuclear matter effects split T_{eff} of kaon upward and that of antikaon downward proportional to the colliding nucleus size

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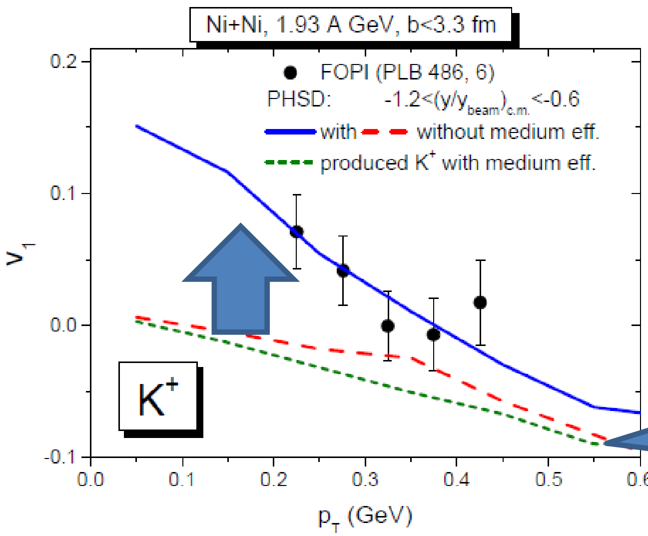
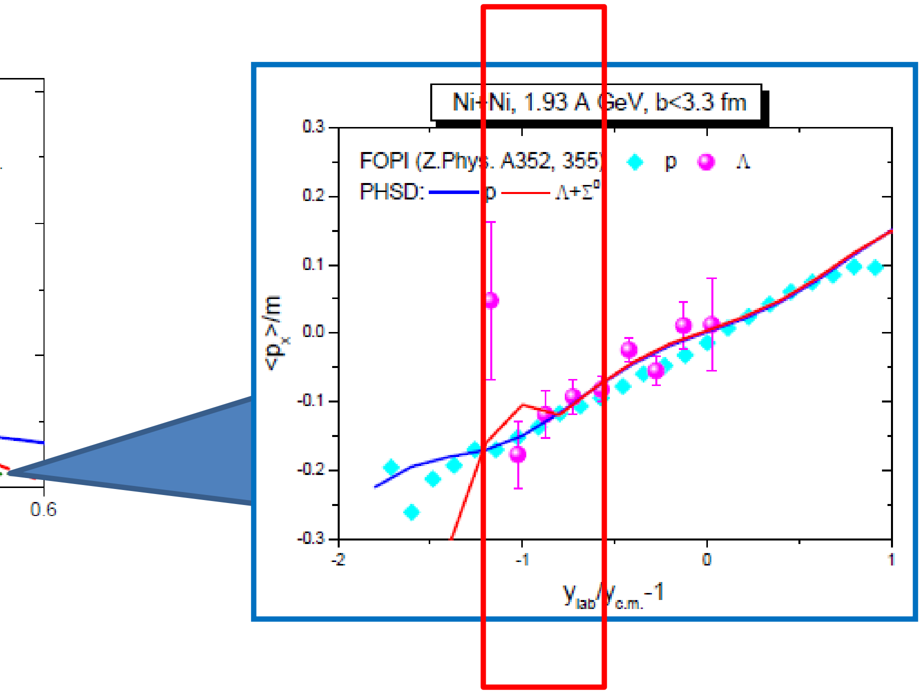
Directed flow (v1)





1. V1 of initial kaon follows that of nucleons because kaon is mostly produced through NN scattering
2. Repulsive force pushes v1 upward
3. Attractive force pulls down v1 of antikaon

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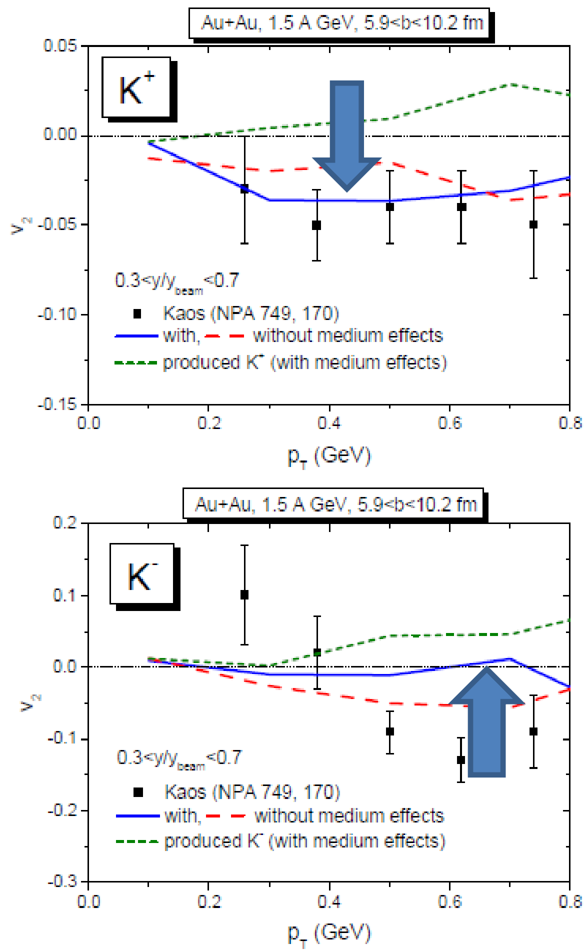
Elliptic flow (v2)



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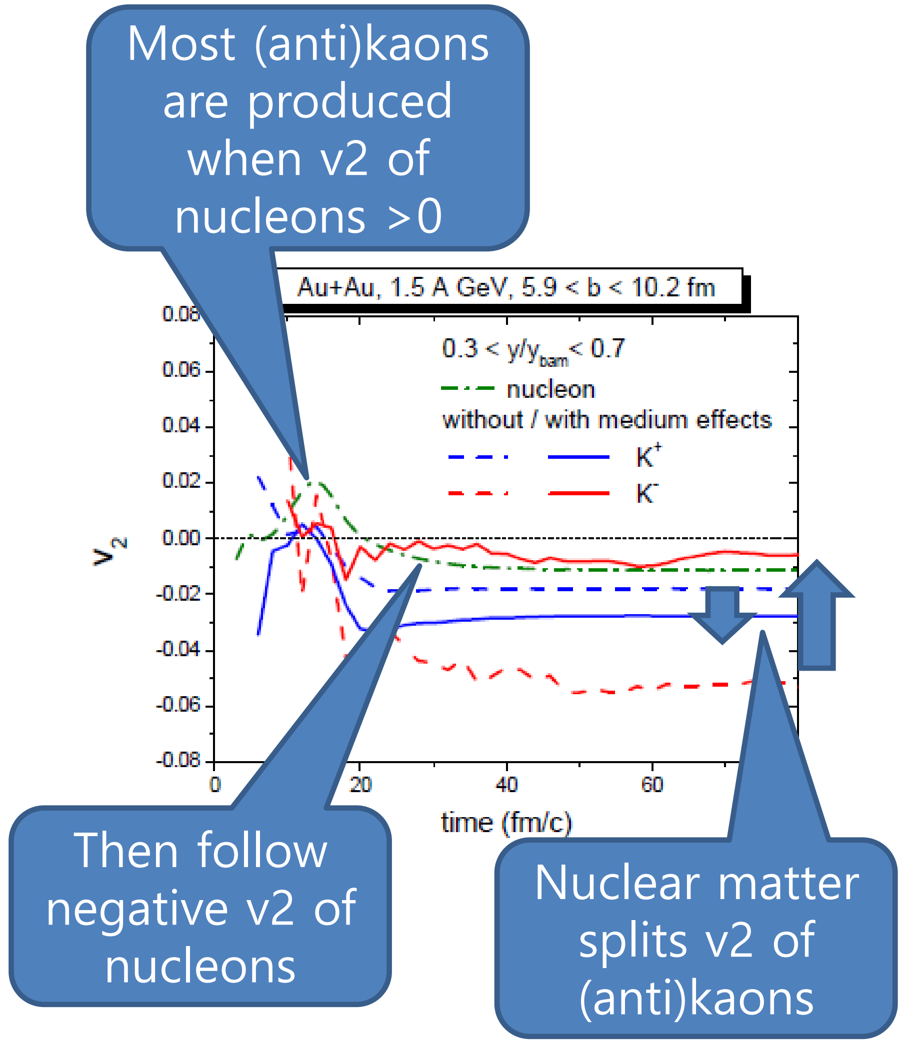
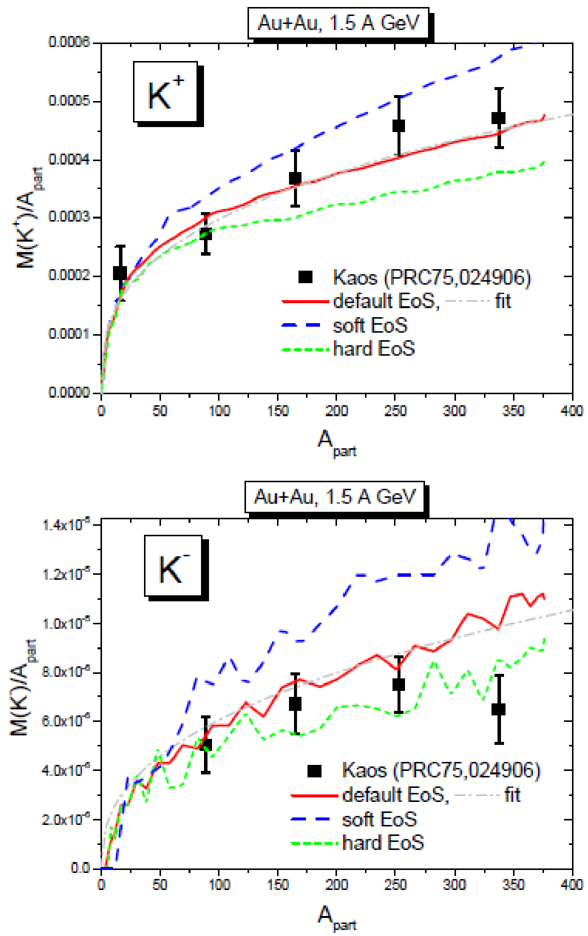


Equation of State (EoS) of nuclear matter



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Skyrme potential [92] parameterized by

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

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

the 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

4. Summary

- We have investigated strangeness production in heavy-ion collisions around the threshold energy between 1-2 A GeV within Parton-Hadron-String Dynamics (PHSD 4.5) transport approach with off-shell propagation based on Kadanoff-Baym Eq. and the detailed balance for 2↔3 interactions
- In-medium effects on antikaon are realized by G-matrix approach and those on kaon by a simple linear repulsive nuclear potential
- The results have been compared with experimental data from the Kaos, FOPI and HADES Collaborations.
- Our findings

1. The kaon nuclear potential increases the threshold energy for kaon production → kaon production is suppressed
2. Since kaon nuclear potential is repulsive, it makes kaon spectrum harder, and y-distribution broader
3. The Kbar spectral function broadens in a medium without drastic changes of pole mass → Kbar production is still enhanced
4. Since antikaon potential is attractive, its spectrum becomes soft in nuclear matter, and y-distribution a bit shrinks

5. The nuclear matter effects on (anti)kaon are more prominent in the collision of larger nuclei, for example, Au+Au > C+C

6. v1, v2 of kaon initially follow those of nucleons whose scattering produces kaon, and then are pushed away in forward/backward rapidities for v1 and in mid-rapidity for v2 because of the repulsive force

7. The effects on antikaon is opposite due to the attractive nuclear potential

8. Equation of State (EoS) also affects (anti)kaon production: soft EoS enhances and hard EoS suppresses the production of (anti)kaons;

Within PHSD and G-matrix approach, moderate EoS (K=300 MeV) reproduces experimental data better

Thank you for your attention!