Open and hidden strangeness production in heavy-ion collisions

Taesoo Song (GSI, Darmstadt)

in collaboration with **Joerg Aichelin, Elena Bratkovskaya**

(SUBATECH, Nantes & GSI, Darmstadt & Frankfurt Uni.)

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1. Introduction

- Strangeness is **a produced flavor** in heavy-ion collision (colliding nuclei themselves do not have strangeness)
- **Strangeness enhancement** was proposed as a signature of QGP formation, for $s\bar{s}$ production is easier than $K\bar{K}$ production
- Strangeness in nuclear matter is related to the **EoS of neutron star** (hyperon puzzle in neutron star)

- In this study we use the **self-consistent coupled-channel unitarized scheme** based on a SU(3) chiral Lagrangian (T-matrix or G-matrix) for $\bar{K}B$ interactions and ϕB interactions
- They are applied to heavy-ion collisions by the help of **parton-hadron-string dynamics (PHSD)**

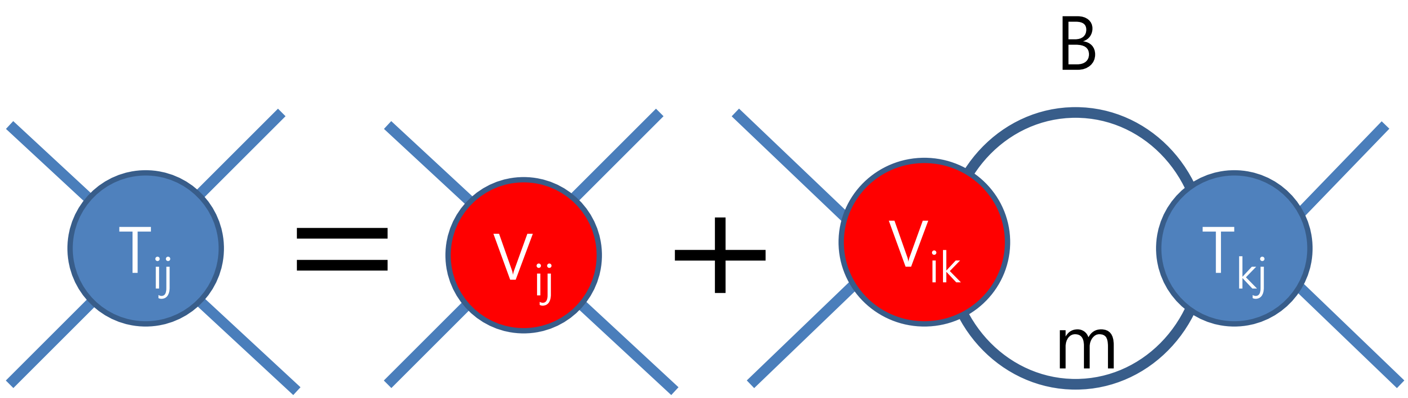
2. Self-consistent coupled-channel unitarizing method (T-matrix, G-matrix)

Self-consistent unitarization (T-matrix)

$V_{ij}^{s} = -C_{ij}\frac{1}{4f^2}\bar{u}(p')\gamma^{\mu}u(p)(k_{\mu}+k'_{\mu}),$ from SU(3) chiral Lagrangian

(S=-1, I_3=0) $i, j = K^-p, \overline{K^0}n, \pi^0\Lambda, \pi^0\Sigma^0, \eta\Lambda, \eta\Sigma^0, \pi^+\Sigma^-, \pi^-\Sigma^+, K^+\Xi^-, K^0\Xi^0$

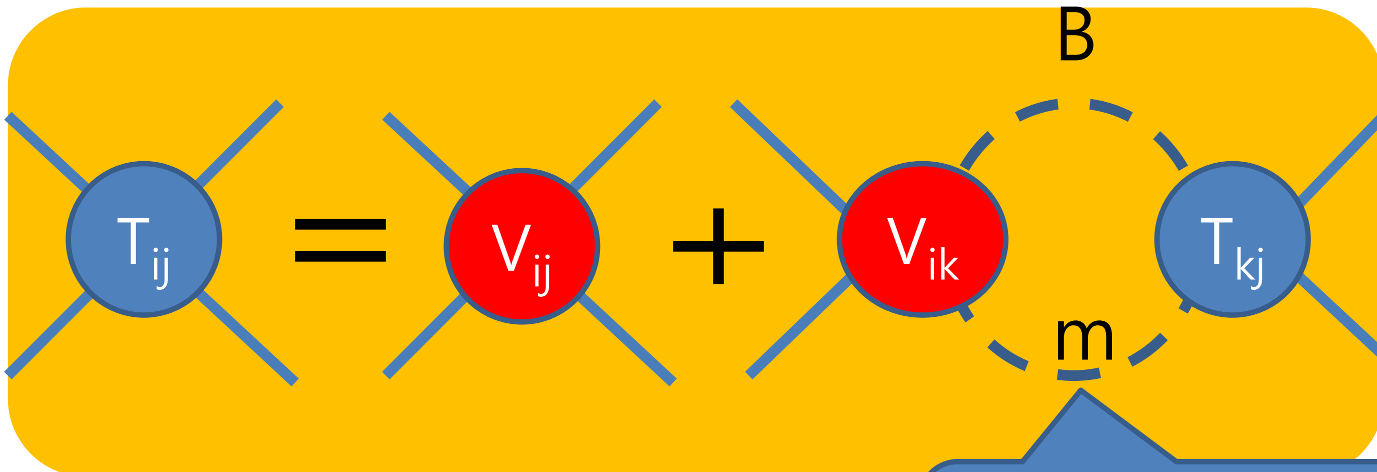
(S=-1, I_3=-1) $i, j = K^-n, \pi^0\Sigma^-, \pi^-\Sigma^0, \pi^-\Lambda, \eta\Sigma^-, K^0\Xi^-$



$N \times N$ equations $N \times N$ variables (T_{ij})

Tolos et al., NPA 690 (2001) 547

Self-consistent unitarization (G-matrix) in nuclear medium



dressing of B and m propagators, and Pauli blocking to B in medium

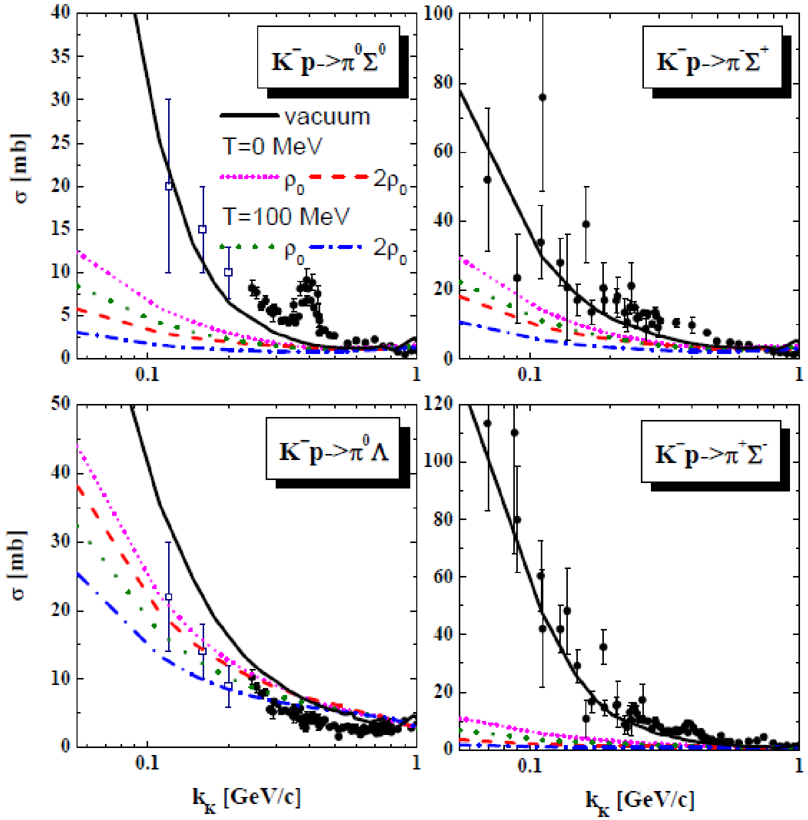
In vacuum

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

At finite T, μ

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

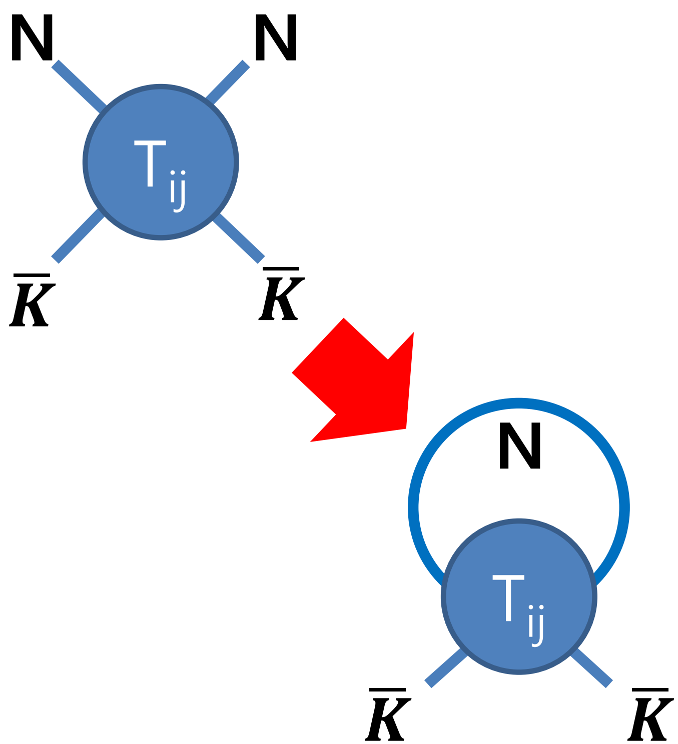
Comparison with Exp. data



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

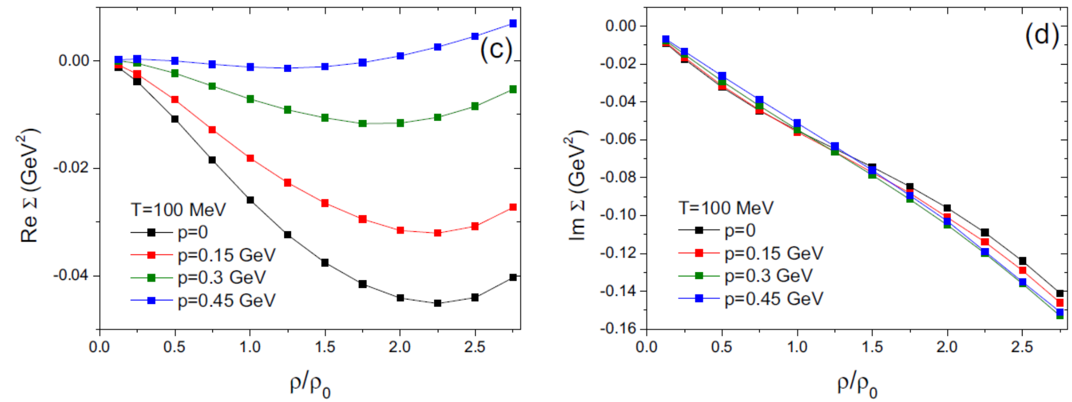
D. Cabrera, et al. PRC 90, 055207 (2014),
T. Song et al. PRC 103, 044901 (2021)

Real & imaginary self energy of $\bar{K}$ $(K^-, \bar{K}^0)$



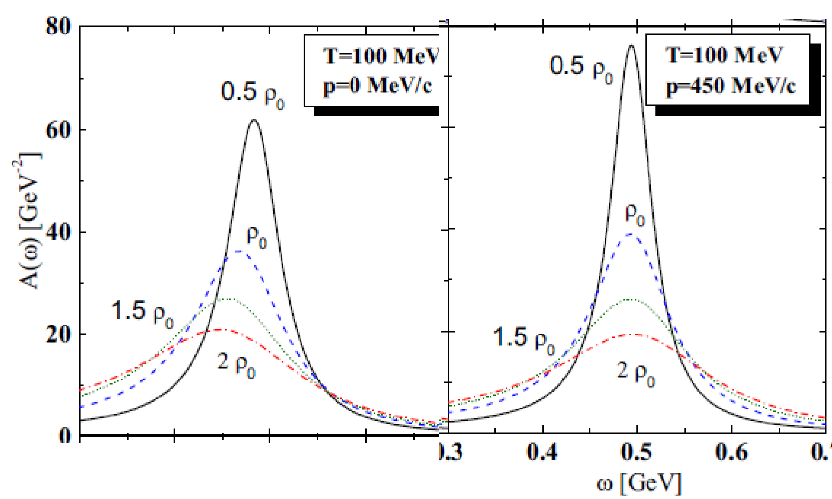
By connecting two N legs,
the self energy of $\bar{K}$ is obtained

$$\Pi^L_{\bar{K}}(q_0, \vec{q}; T) = 4 \int \frac{d^3p}{(2\pi)^3} n_N(\vec{p}, T)\, \bar{T}^L_{\bar{K}N}(P_0, \vec{P}; T)$$

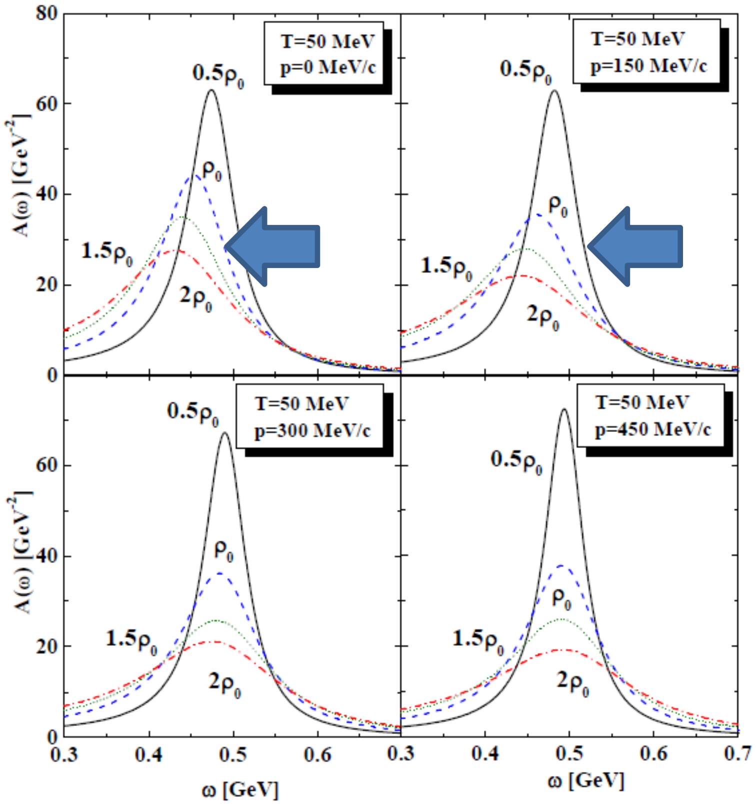


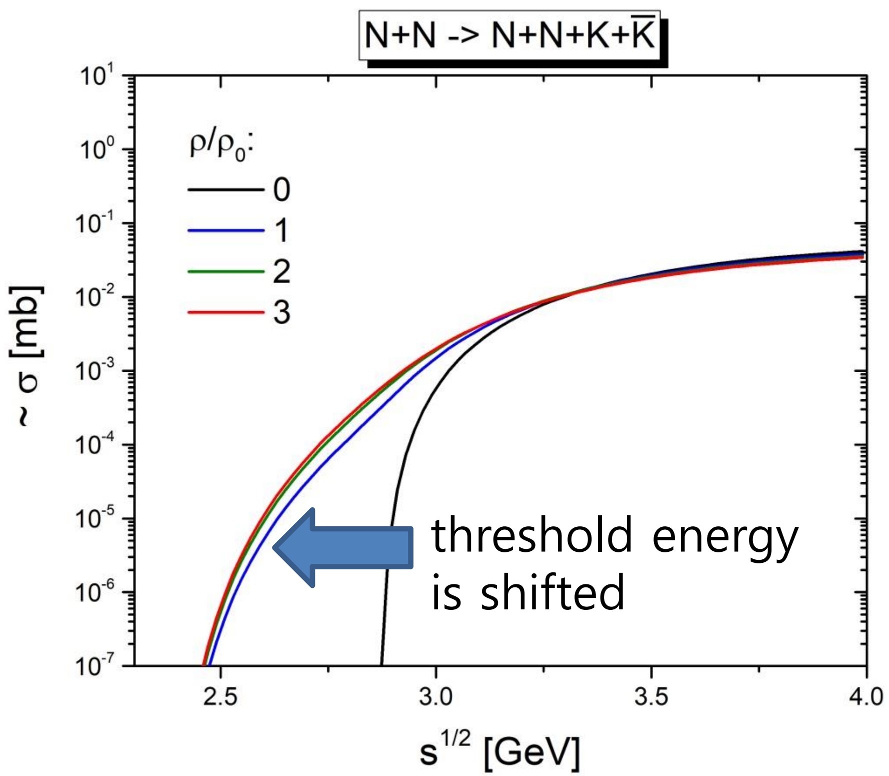
Spectral function from
self-energy

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



The mass shift and/or the width broadening of $\bar{K}$ in medium enhances $\bar{K}$ production





2. Parton-Hadron-String Dynamics (PHSD)

Parton-Hadron-String Dynamics (PHSD) is a non-equilibrium microscopic transport approach for the description of dynamics of **strongly-interacting hadronic and partonic matter** produced in heavy-ion collisions

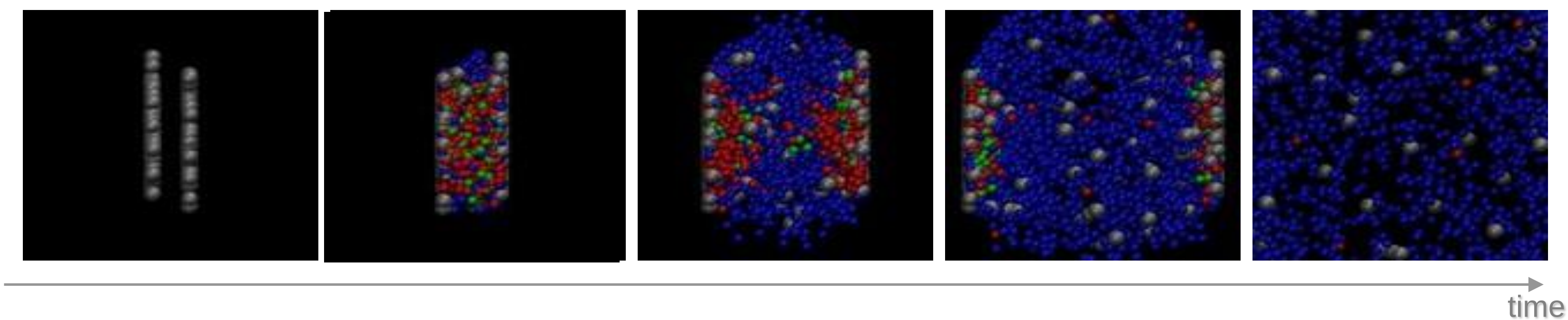
Dynamics: based on the solution of generalized off-shell transport equations derived from **Kadanoff-Baym many-body theory** (beyond semi-classical BUU)

Initial state: Au+Au

Quark-Gluon Plasma: lQCD EoS
non-perturbative QCD - quasiaprticles

Dynamical
Hadronization

Hadronic interactions
→final hadrons + leptons



PHSD provides a good description of 'bulk' hadronic and electromagnetic observables from SIS to LHC energies

PHSD: W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; P. Moreau et al., PRC100 (2019) 014911

Off-shell particle ($\bar{K}$) propagation

Off-shell propagation of $\bar{K}$ from Kadanoff Baym Eq.

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

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

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

or

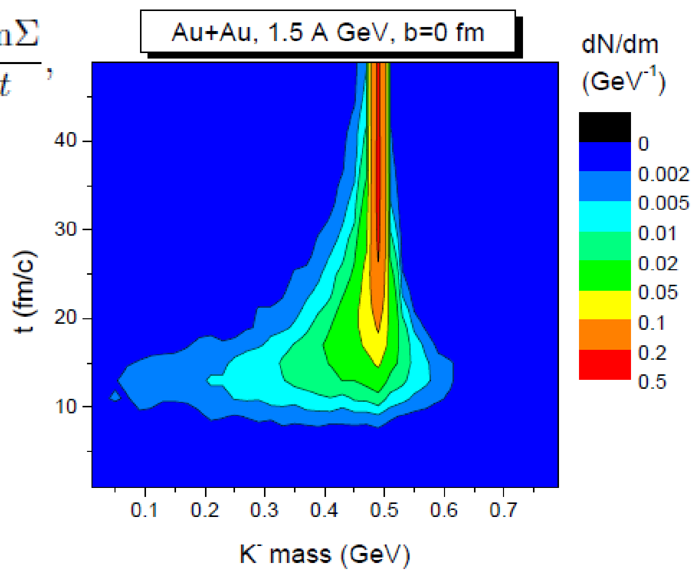
$$\frac{dM^2}{dt} = \frac{M^2-M_0^2}{\mathrm{Im}\Sigma}\frac{d\mathrm{Im}\Sigma}{dt},$$

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
$\mathrm{Im}\Sigma$, $\nabla_p \mathrm{Re}\Sigma \rightarrow 0$



W. Cassing et al., NPA 727, 59 (2003)
T. Song et al. PRC 103, 044901 (2021)

3. K and $\bar{K}$ production in PHSD

$\bar{K}$ in PHSD

- G-matrix method
- Off-shell propagation

K in PHSD

- Repulsive potential in matter

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

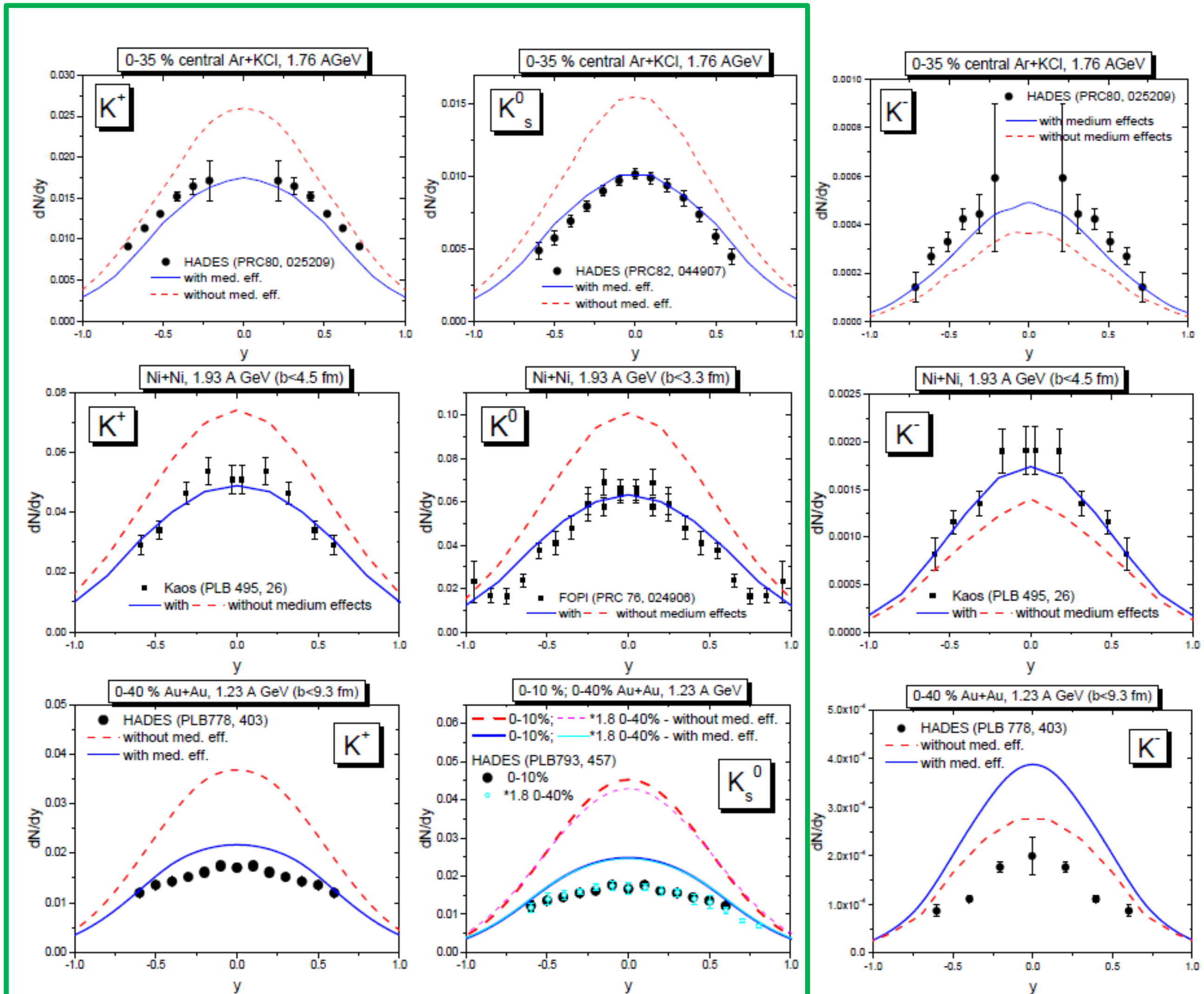
is related to the increase of effective mass

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

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

Rapidity distributions of (anti)kaons

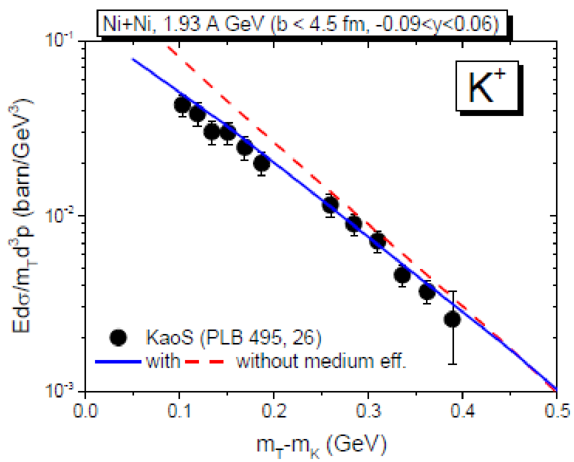
Nuclear matter effects suppress kaon production

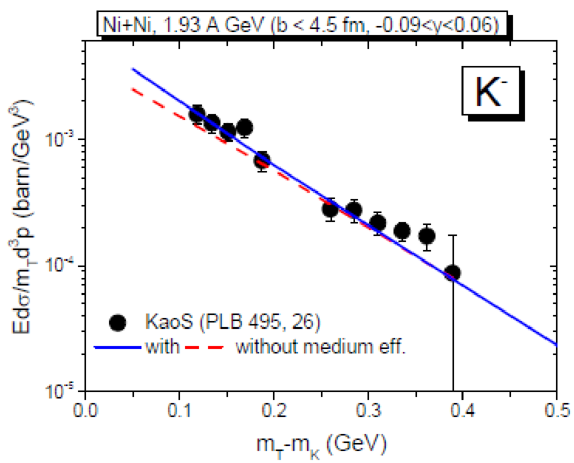


Nuclear matter effects enhance antikaon production

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

m_T spectra of K & $\bar{K}$ in central Ni+Ni collisions at E=1.93 A GeV



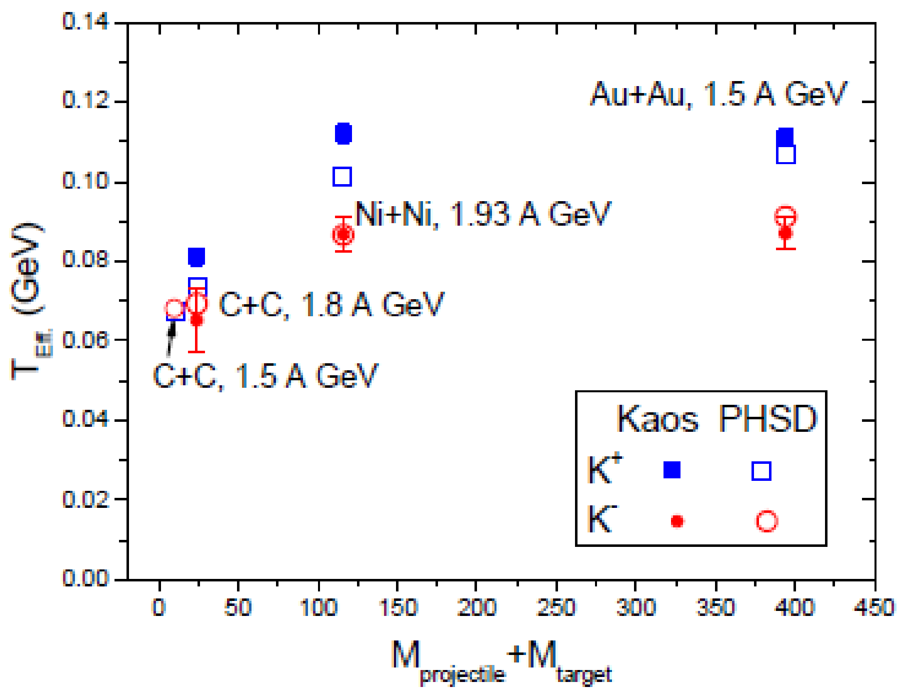


- Nuclear matter suppresses kaon production and hardens spectrum, while it enhances antikaon production and softens spectrum

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

Effective temperature

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

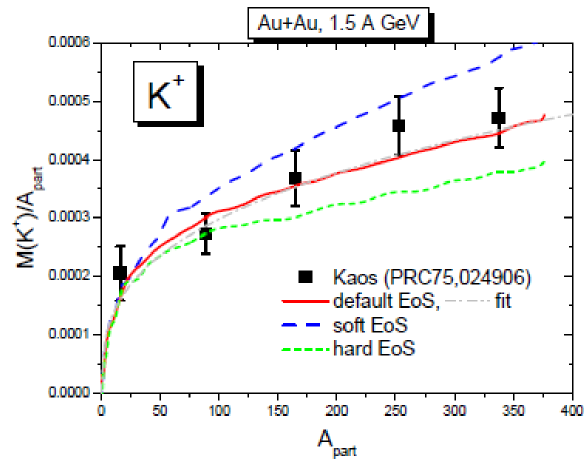


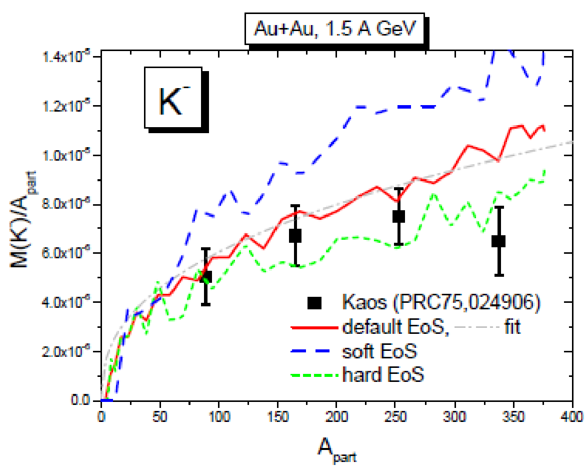
- Effective temperature increases with colliding nucleus size because of the stronger flow in larger nucleus collisions

- Nuclear matter effects split T_{eff} of kaon upward and that of antikaon downward proportional to the colliding nucleus size

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

Equation of State (EoS) of nuclear matter





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

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

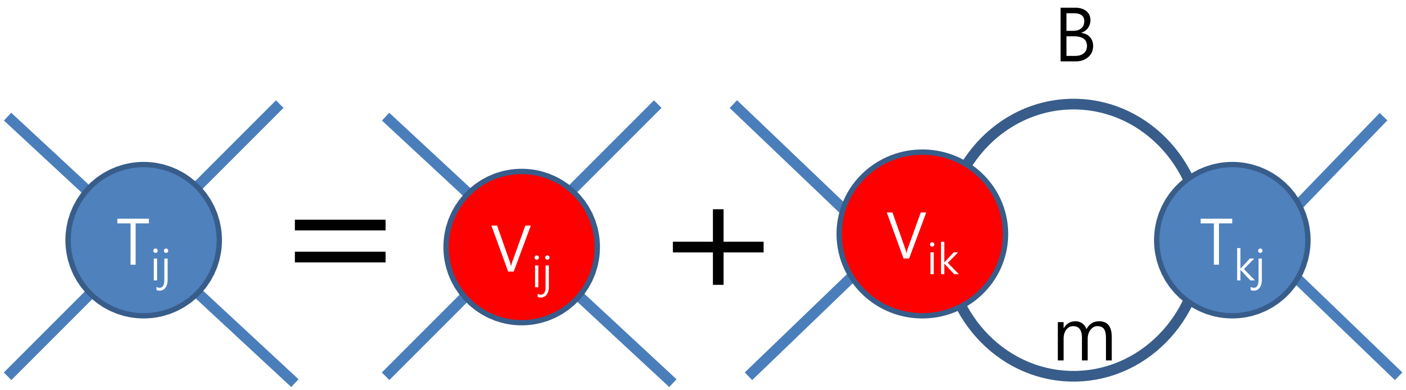
4. Φ meson production in PHSD

Self-consistent unitarization (T-matrix)

$V_{ij}^s = -C_{ij}\frac{1}{4f^2}\bar{u}(p')\gamma^\mu u(p)(k_\mu + k'_\mu),$ from SU(3) chiral Lagrangian

(S=0, I_3=1/2) $i = \eta N,\ K\Lambda,\ K\Sigma,\ \rho N,\ \rho\Delta,\ K^*\Lambda,\ K\Sigma^*,\ K^*\Sigma,\ K^*\Sigma^*$, j=$\phi N$

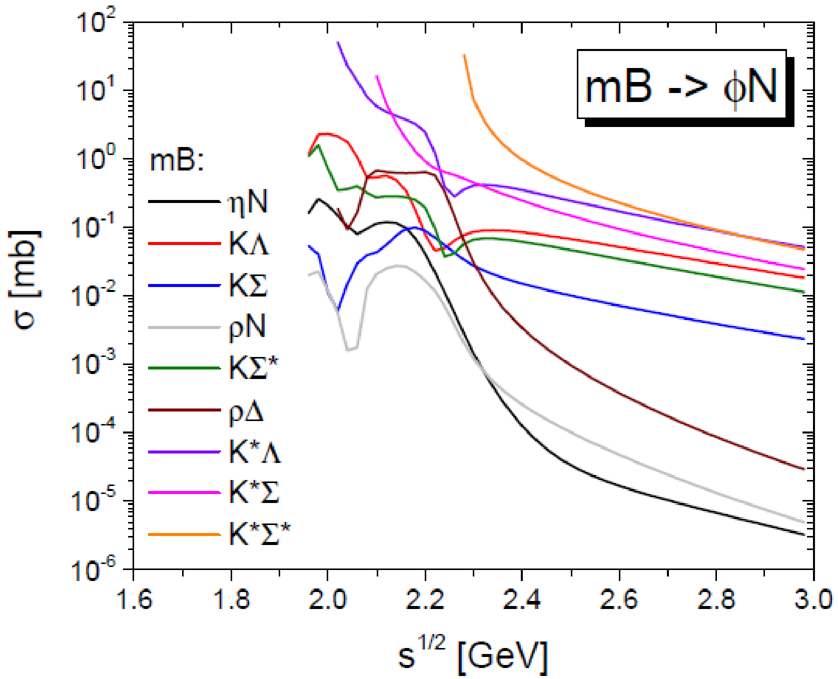
(S=0, I_3=3/2) $i = K\Sigma,\ \rho N,\ \eta\Delta,\ K\Sigma^*,\ \rho\Delta,\ K^*\Sigma, K^*\Sigma^*$, j=$\phi\Delta$

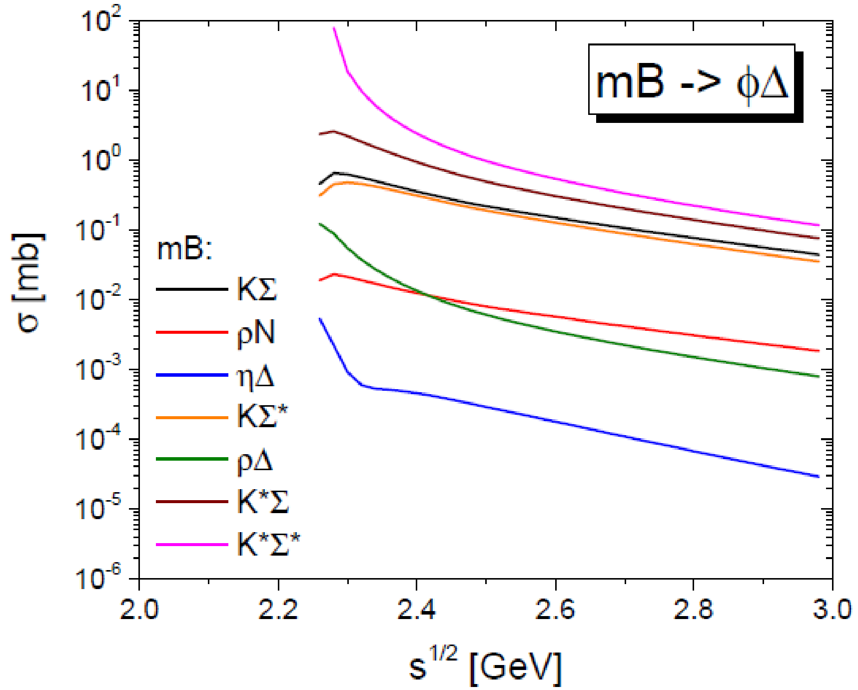


$N \times N$ equations $N \times N$ variables (T_{ij})

Tolos et al., NPA 690 (2001) 547

Scattering cross section for Φ production





T.Song et al., PRC 106, 024903 (2022)

Spectral width broadening of Φ in medium

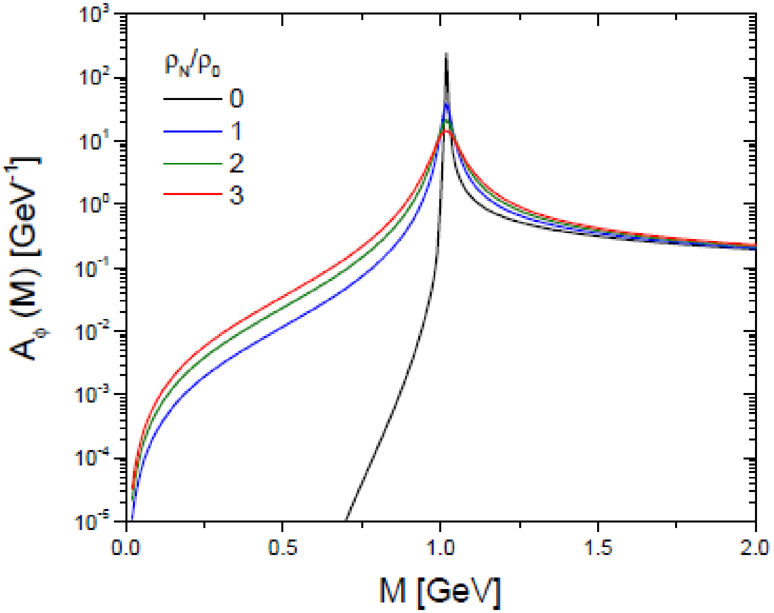
- Vacuum width

$$\Gamma_\phi(M) \simeq \Gamma^{exp}_{\phi\to\rho\pi(3\pi)} \frac{\Gamma_{\phi\to\rho\pi(3\pi)}(M)}{\Gamma_{\phi\to\rho\pi(3\pi)}(M_0)} + \Gamma^{exp}_{\phi\to K\bar{K}} \left(\frac{M_0}{M}\right)^2 \left(\frac{q}{q_0}\right)^3 \theta(M-2m_K),$$

- Collisional width

$$\Gamma_{coll}(M,|\vec{p}|,\rho_N) = \gamma\ \rho_N < v\ \sigma^{tot}_{VN} > \approx \alpha_{coll} \frac{\rho_N}{\rho_0}$$

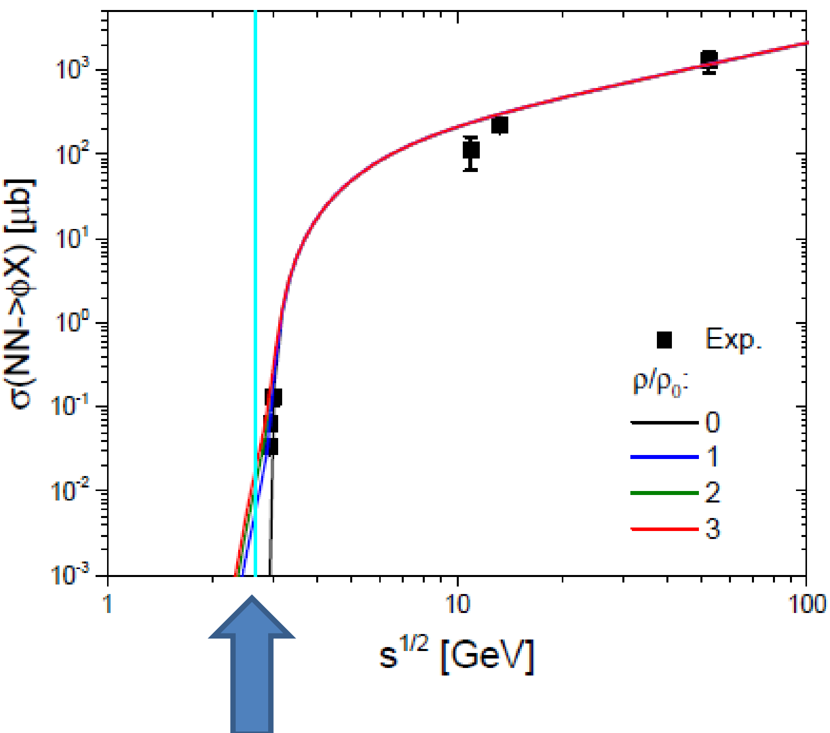
$$\Gamma^*_V(M,|\vec{p}|,\rho_N) = \Gamma_V(M) + \Gamma_{coll}(M,|\vec{p}|,\rho_N).$$



25 MeV from QCD sum rule
P. Gubler, NPA **954**, 125 (2016)

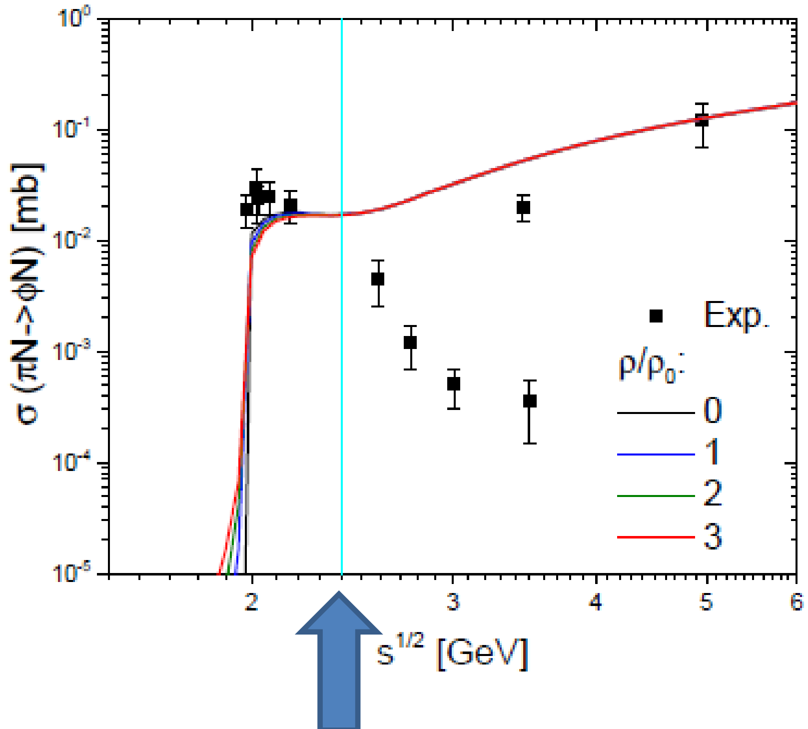
Other cross sections for Φ production

N+N→Φ+X



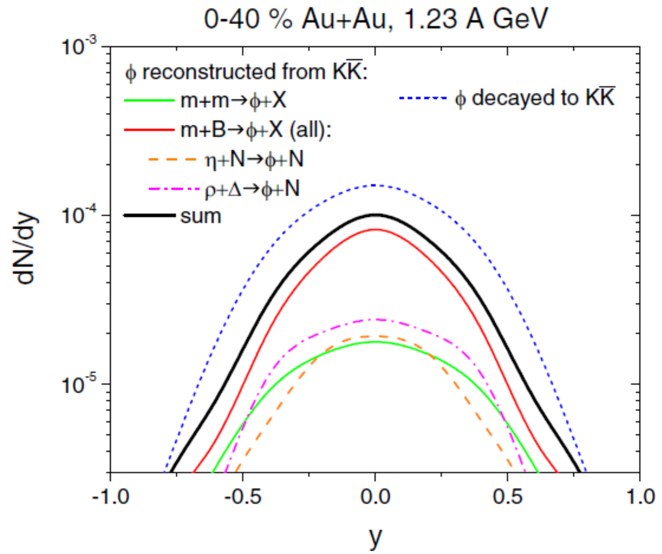
Threshold energy for N+N string fragmentation

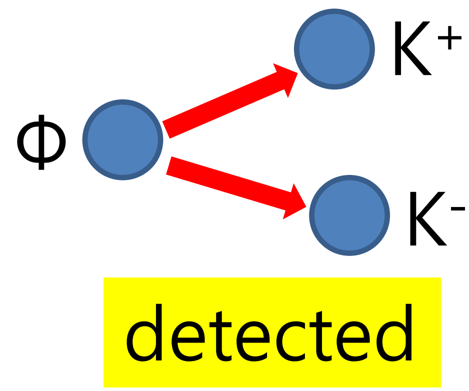
π+N→Φ+X

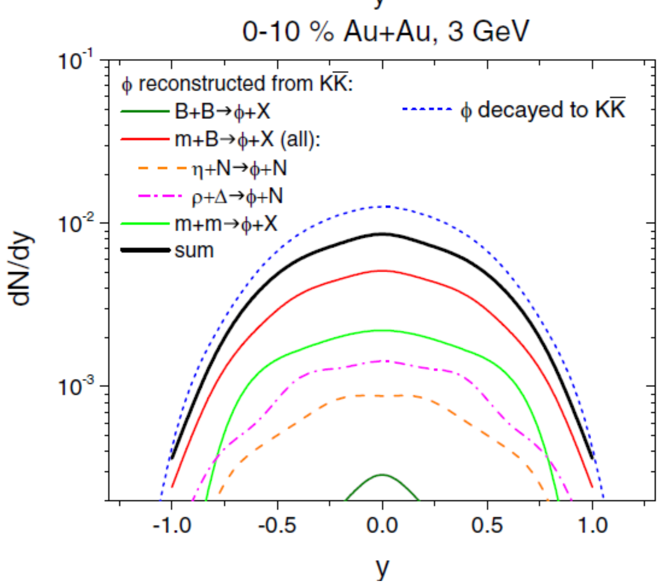


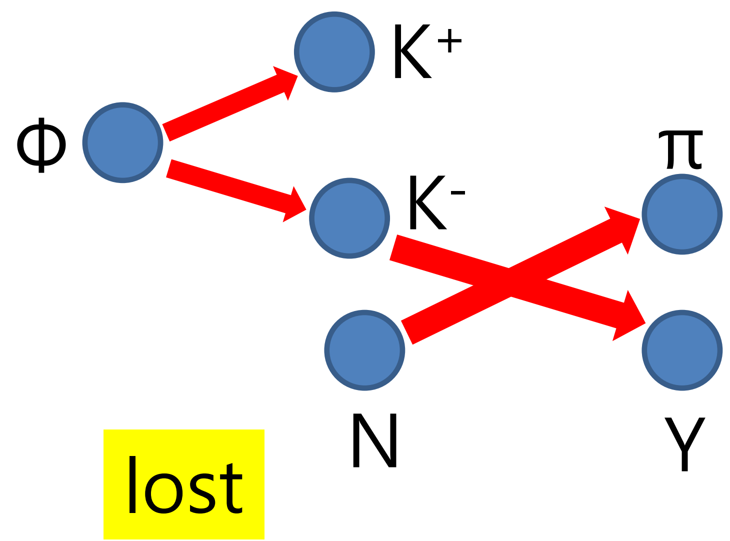
Threshold energy for π+N string fragmentation

Reconstruction of Φ from K^+ K^- pairs

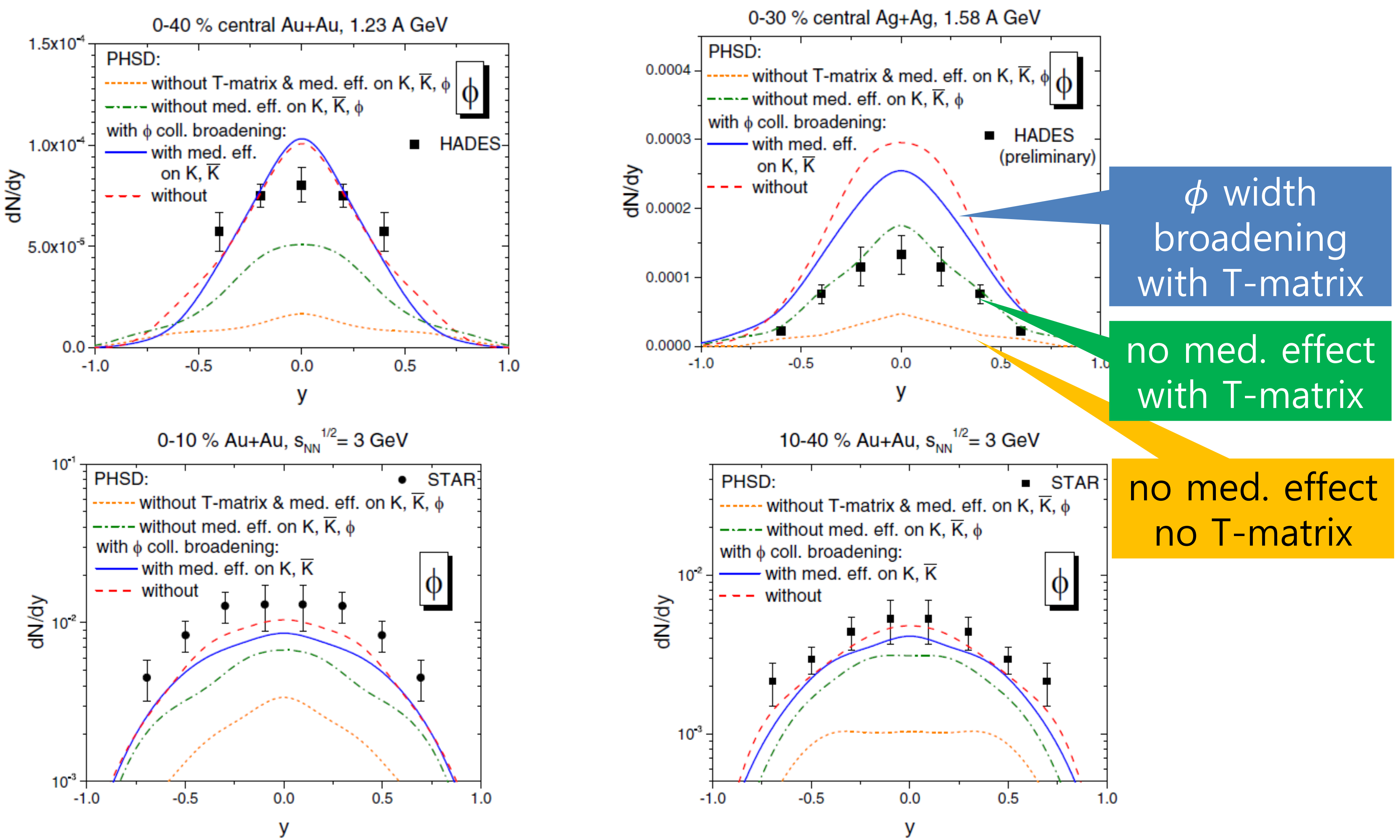






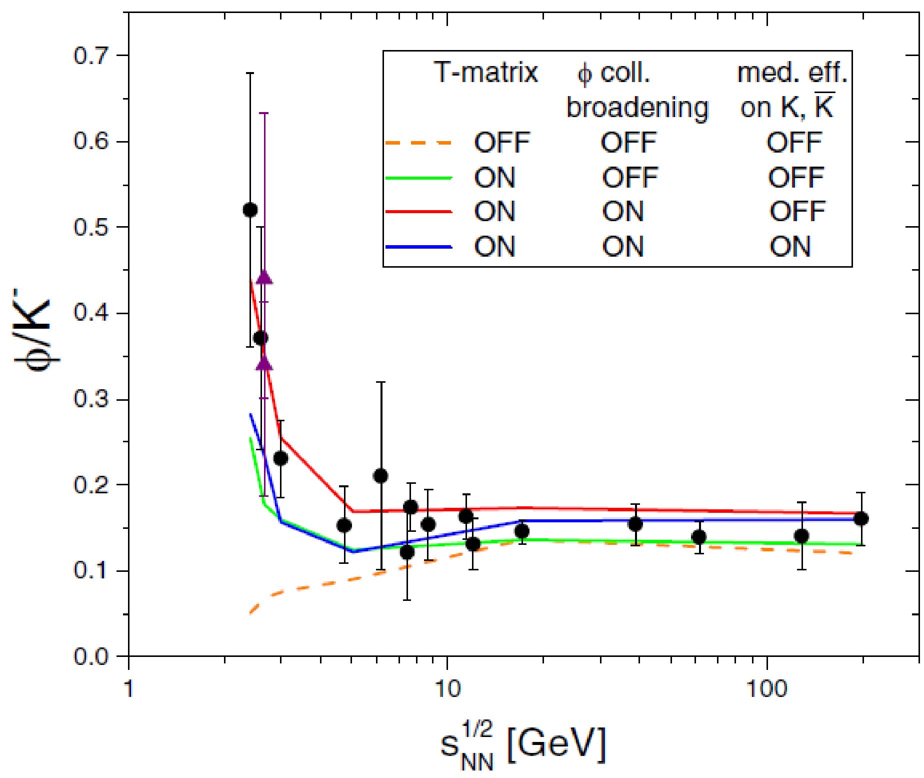


Comparison with experimental data



T.Song et al., PRC 106, 024903 (2022)

Φ/K⁻ ratio in heavy-ion collisions



Φ width broadening related to the chiral symmetry restoration is necessary to explain the experimental data on the ratio of Φ/K⁻

T.Song et al., PRC 106, 024903 (2022)

5. Summary

- In order to study strangeness production in heavy-ion collisions (in nuclear matter) we have combined the self-consistent coupled-channel unitarizing method (T, G-matrix) and PHSD with off-shell propagation
- We have found K^+ production is suppressed and its spectrum hardens in medium while K^- production is enhanced and its spectrum softens, which is consistent with experimental data from HADES, KaoS, FOPI
- We have also studied Φ production by using the same T-matrix & width broadening in medium (chiral symmetry restoration)
- We have found the width broadening is necessary to explain the experimental data from HADES and STAR

Thank you for your attention!

Contents

- Introduction
- self-consistent coupled-channel unitarizing method (T, G-matrix)
- Parton-Hadron-String Dynamics (PHSD)
- K and $\overline{K}$ production in PHSD
- Φ meson production in PHSD
- Summary

The lowest-order SU(3) chiral Lagrangian

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

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

Spin ½+ SU(3) 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

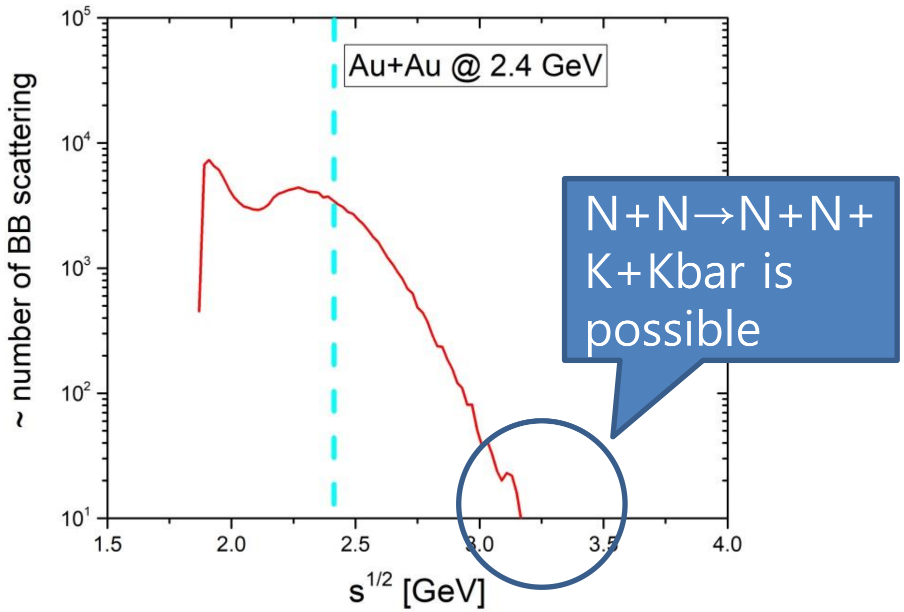
$$\Phi = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{6}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{6}\eta & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{pmatrix}$$

Anti-kaon production below threshold energy

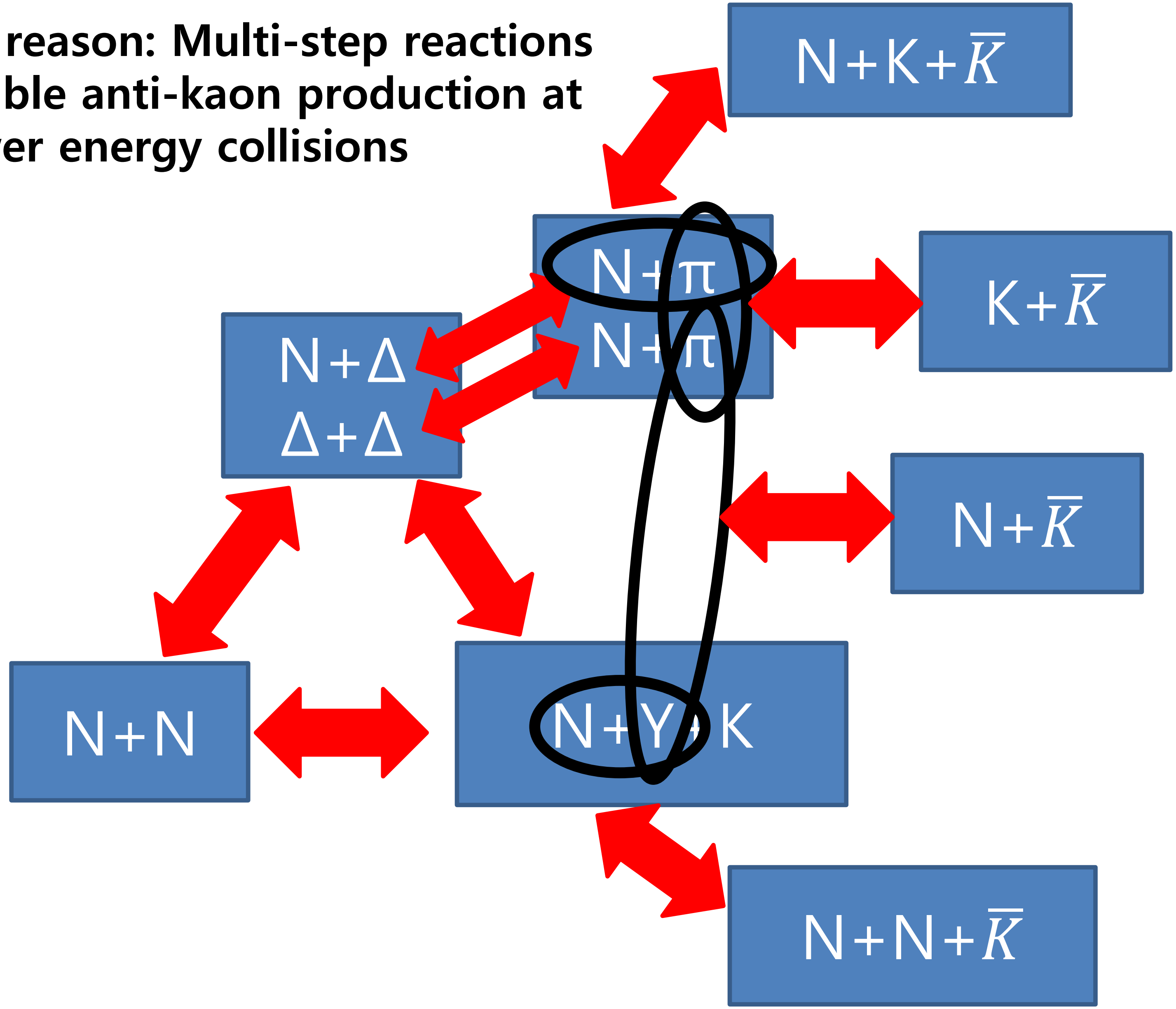
- In elementary scattering about $s^{1/2}$=3 GeV of energy is required to produce anti-kaon
- **N+N→N+N+K+Kbar**

- However, anti-kaon can be produced at lower energy in heavy-ion collisions

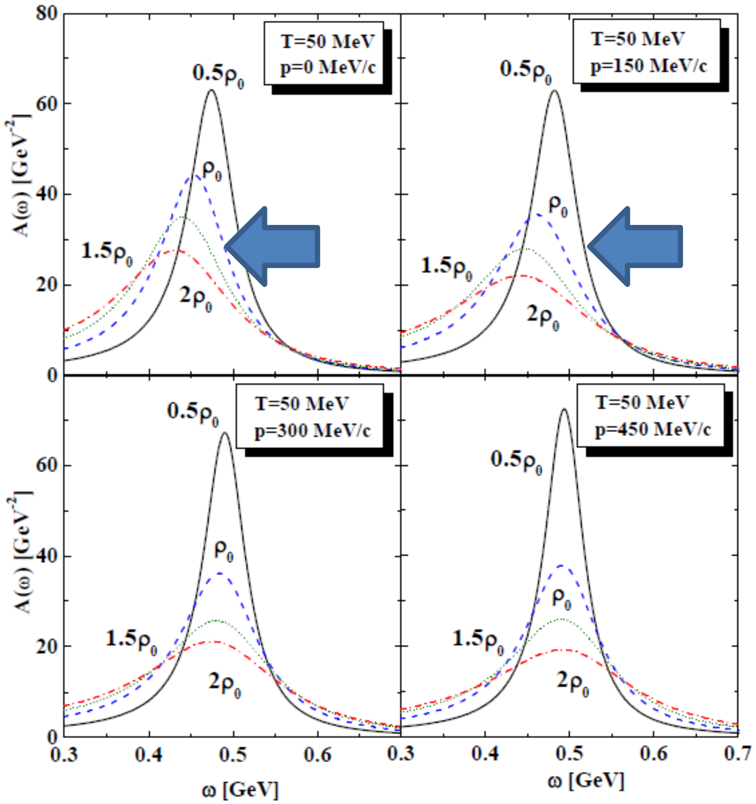
1st reason: B+B scattering energy distribution (due to the Fermi momentum, secondary collisions, baryon excitation and so on)

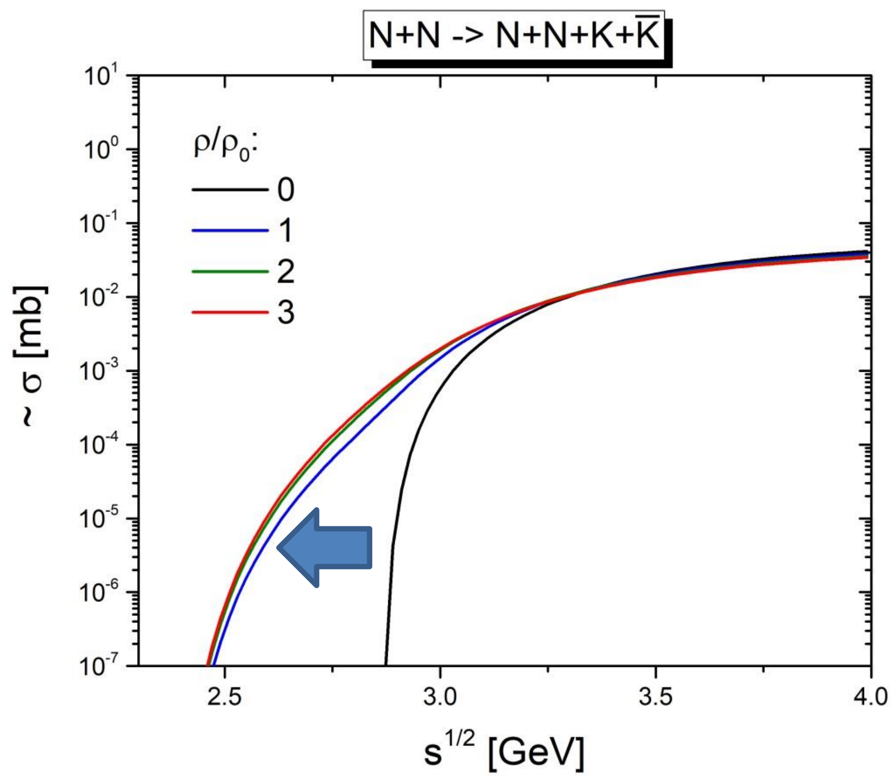


2nd reason: Multi-step reactions enable anti-kaon production at lower energy collisions



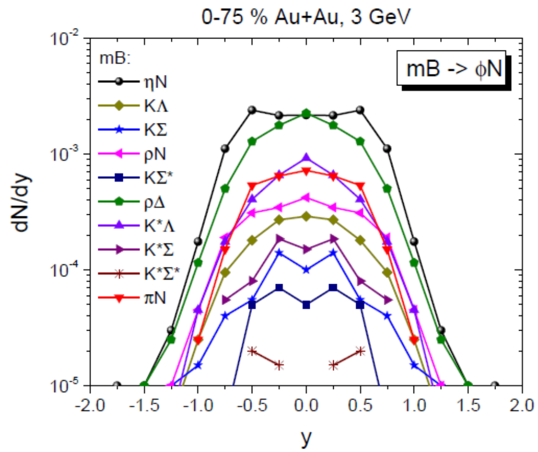
3^{rd} reason: threshold energy is shifted to a lower energy due to the shift of the pole mass and/or the width broadening of anti-kaon in medium

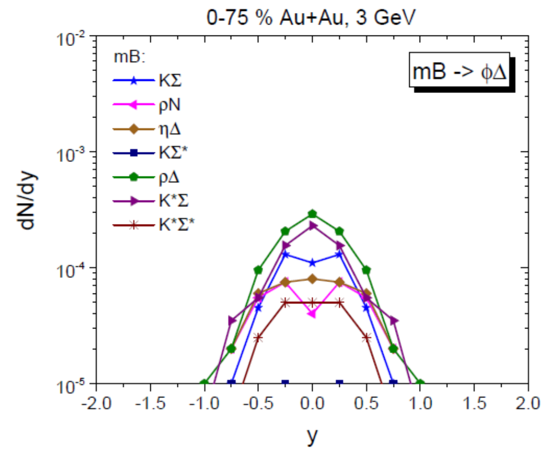




y-distribution of Φ production & absorption in Au+Au collisions at 3 GeV

production





absorption