In-medium effects on hidden strangeness production in heavy-ion collisions

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1. Introduction

- Strangeness is a produced flavor in nuclear collisions
- Strangeness production is enhanced in A+A collisions, compared to p+p collisions
- One example is sub-threshold production of strangeness in A+A collisions by the help of **multistep reactions** & **in-medium modification of hadron properties**, which are absent in p+p collisions
- The strangeness enhancement in A+A collisions at high energy has been suggested as one of QGP signals
- This enhancement is seen not only in open strangeness but also in hidden strangeness (Φ meson)

- In this study we try to understand Φ production in heavy-ion collisions by taking into account **width broadening of Φ meson in medium** & **various m+B scattering channels from T-matrix method** based on the effective chiral lagrangian.
- For the purpose we implement both effects in the PHSD (Parton-Hadron-String Dynamics)

2. In-medium modification of Φ meson

mass shift

width broadening

mass shift + width broadening

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

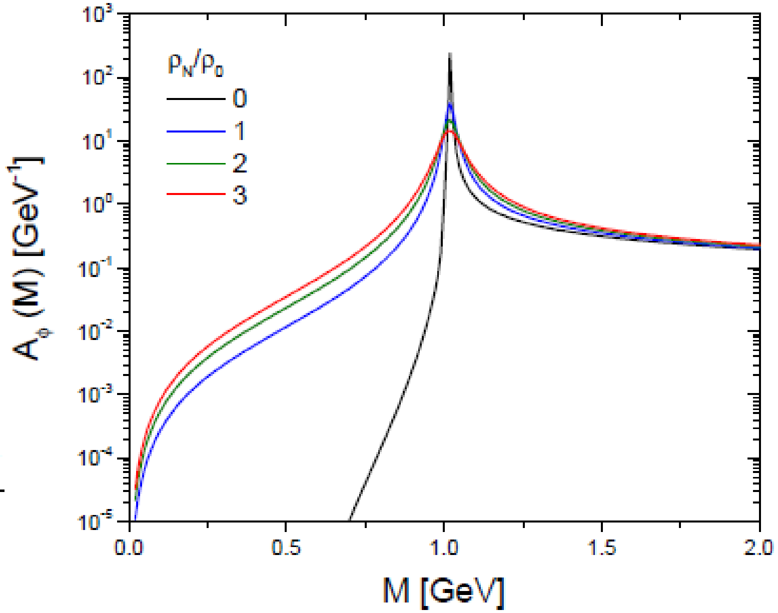
- Vacuum width contributed

from Φ→3π and Φ→K+Kbar

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

- Collisional width

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

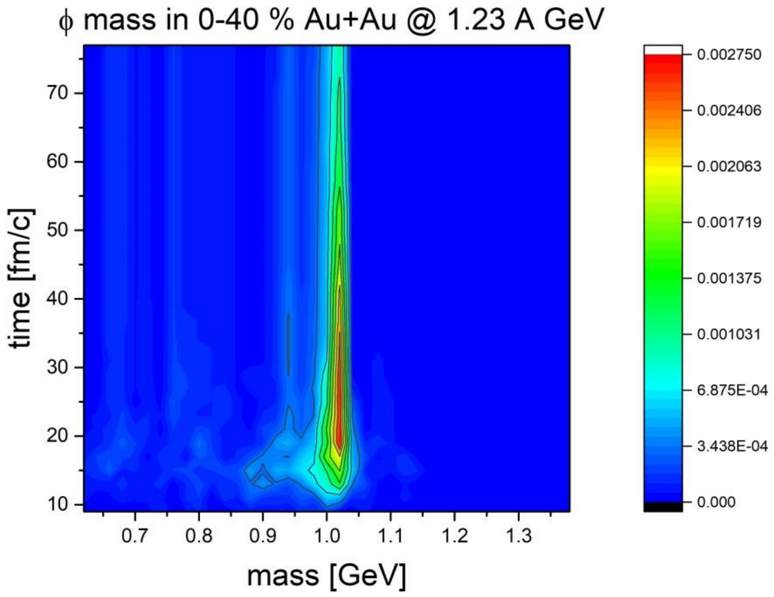


α_{coll}=13.5 MeV from KEK E325

α_{coll} < 40 MeV from hadronic models

We take **25 MeV**

The propagation of off-shell Φ meson in medium



$$\frac{dM_i^2}{dt} = \frac{M_i^2 - M_0^2}{\tilde{\Gamma}_{(i)}} \frac{d\tilde{\Gamma}_{(i)}}{dt}$$

- M_0: pole mass of Φ
- M_i: in-medium mass of Φ
- Γ: spectral width

If $M_i < M_0$, M_i increases toward M_0
If $M_i > M_0$, M_i decreases toward M_0
Finally, M_i converges to the vacuum mass

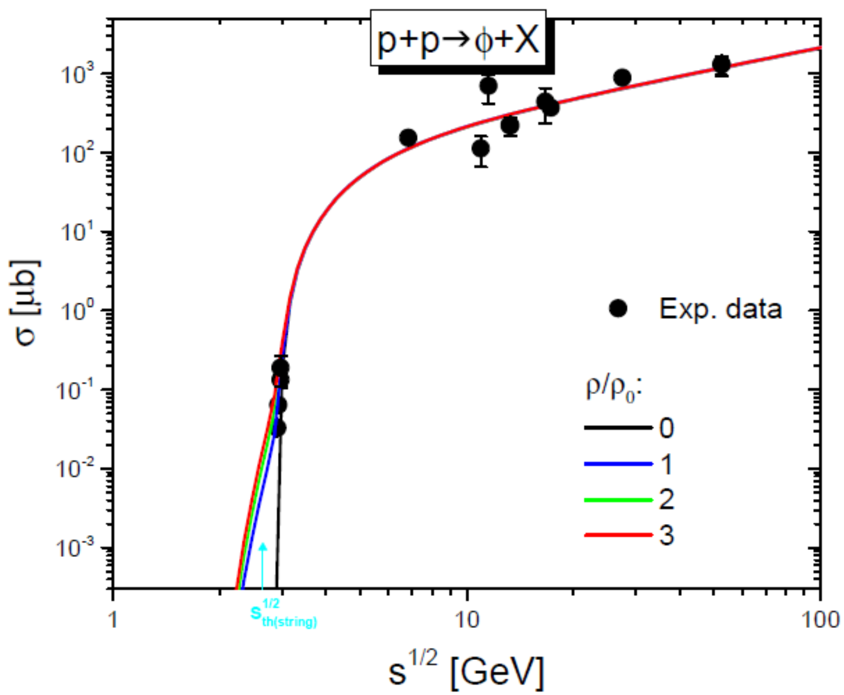
In-medium cross section for Φ production

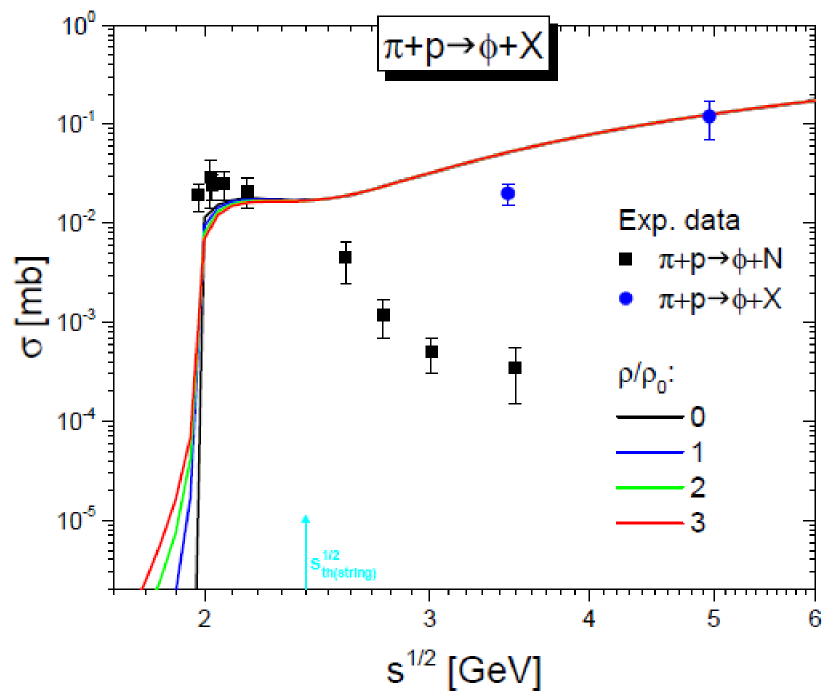
$$\sigma_{NN\to VNN}(s,\rho) = \frac{\int_{M_{min}}^{M_{max}} A_V(M,\rho)\sigma^0_{NN\to VNN}(s,M,\rho)dM}{\int_{M_{min}}^{M_{lim}} A_V(M,\rho)dM.}$$

Φ spectral function

p+p→Φ+X

π+p→Φ+X





Width broadening of Φ meson lowers the threshold energy for Φ production

3. T-matrix for Φ meson production

- From SU(3) Chiral Lagrangian

arXiv:1104.2737 D. Gamermann

$$V_{ij}^{SIJ} = \varepsilon_{ij}^{SIJ} \frac{2\sqrt{s} - M_i - M_j}{4 f_i f_j} \sqrt{\frac{E_i + M_i}{2M_i}} \sqrt{\frac{E_j + M_j}{2M_j}}$$

ε_{ij}^{SIJ}: coefficient as a function of total strangeness(S), total isospin(I), total angular momentum(J) with initial meson-baryon state(i) and final meson-baryon state(j)

For S=0, I_3=1/2, i, j=

$$\eta N,\ K\Lambda,\ K\Sigma,\ \rho N,\ K\Sigma^*,\ \rho\Delta,$$
$$K^*\Lambda,\ K^*\Sigma,\ K^*\Sigma^* \to \phi N,$$

For S=0, I_3=3/2, i, j=

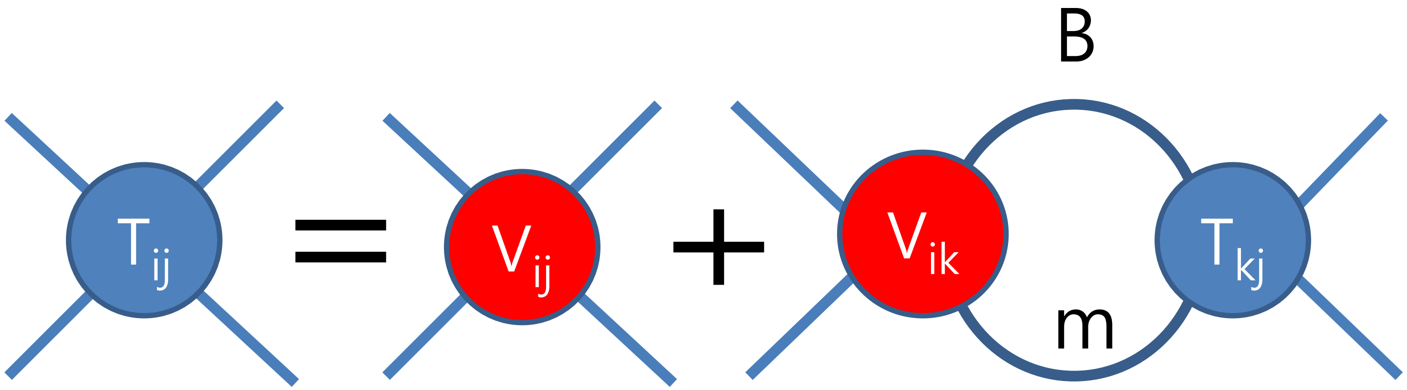
$$K\Sigma,\ \rho N,\ \eta\Delta,\ K\Sigma^*,\ \rho\Delta,$$
$$K^*\Sigma,\ K^*\Sigma^* \to \phi\Delta$$

E_i (E_j): incoming (outgoing) baryon energy in c.m. frame

M_i (M_j): incoming (outgoing) baryon mass

f_i (f_j): decay constant of incoming (outgoing) meson

Self-consistent unitarization



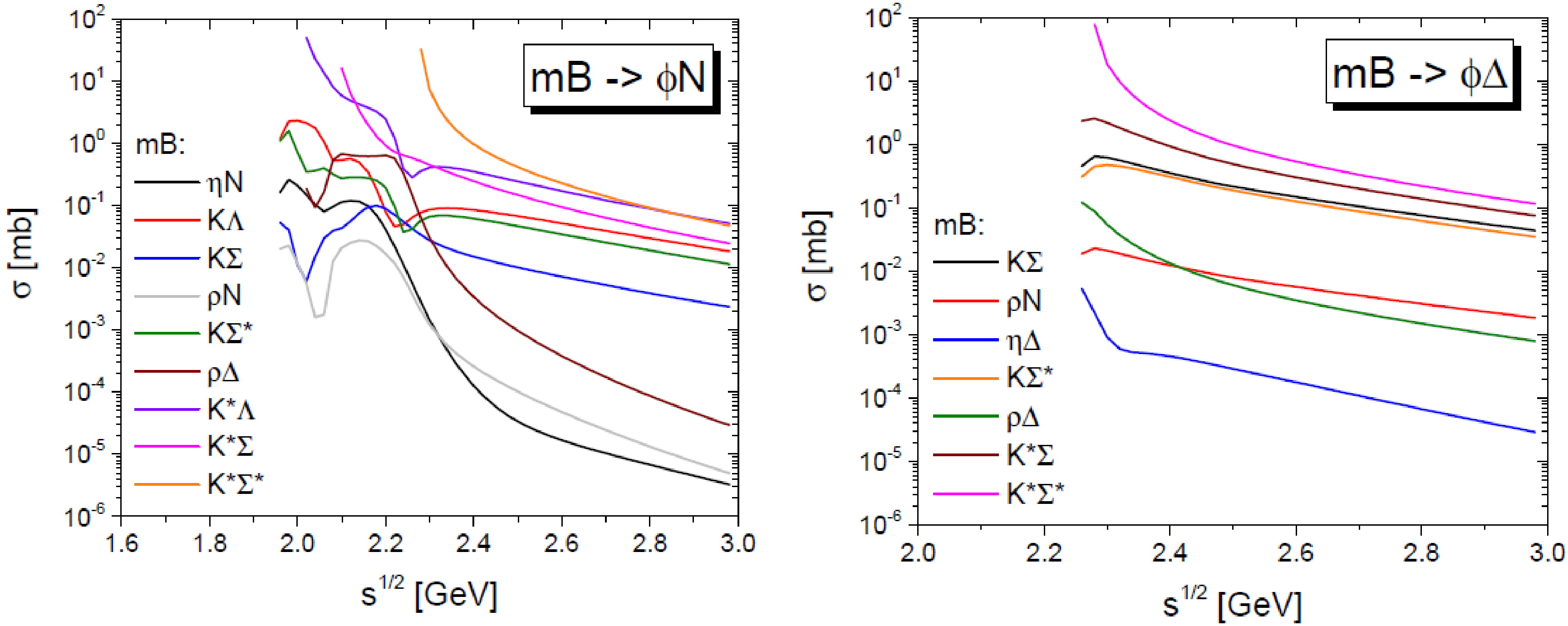
$$T_{ij}^{SIJ} = V_{ij}^{SIJ} + V_{ik}^{SIJ} G_{kk}^{SIJ} T_{kj}^{SIJ}$$

G_{kk}^{SIJ}: : baryon and meson propagators renormalized at $G_{kk}^{SIJ}(s = m_N^2 + m_\pi^2) = 0$

$$T_{ij}^{SIJ} = (1 - V^{SIJ} G^{SIJ})_{ik}^{-1} V_{kj}^{SIJ}$$

where $1_{jk} = \delta_{jk}$.

Scattering cross sections for Φ production

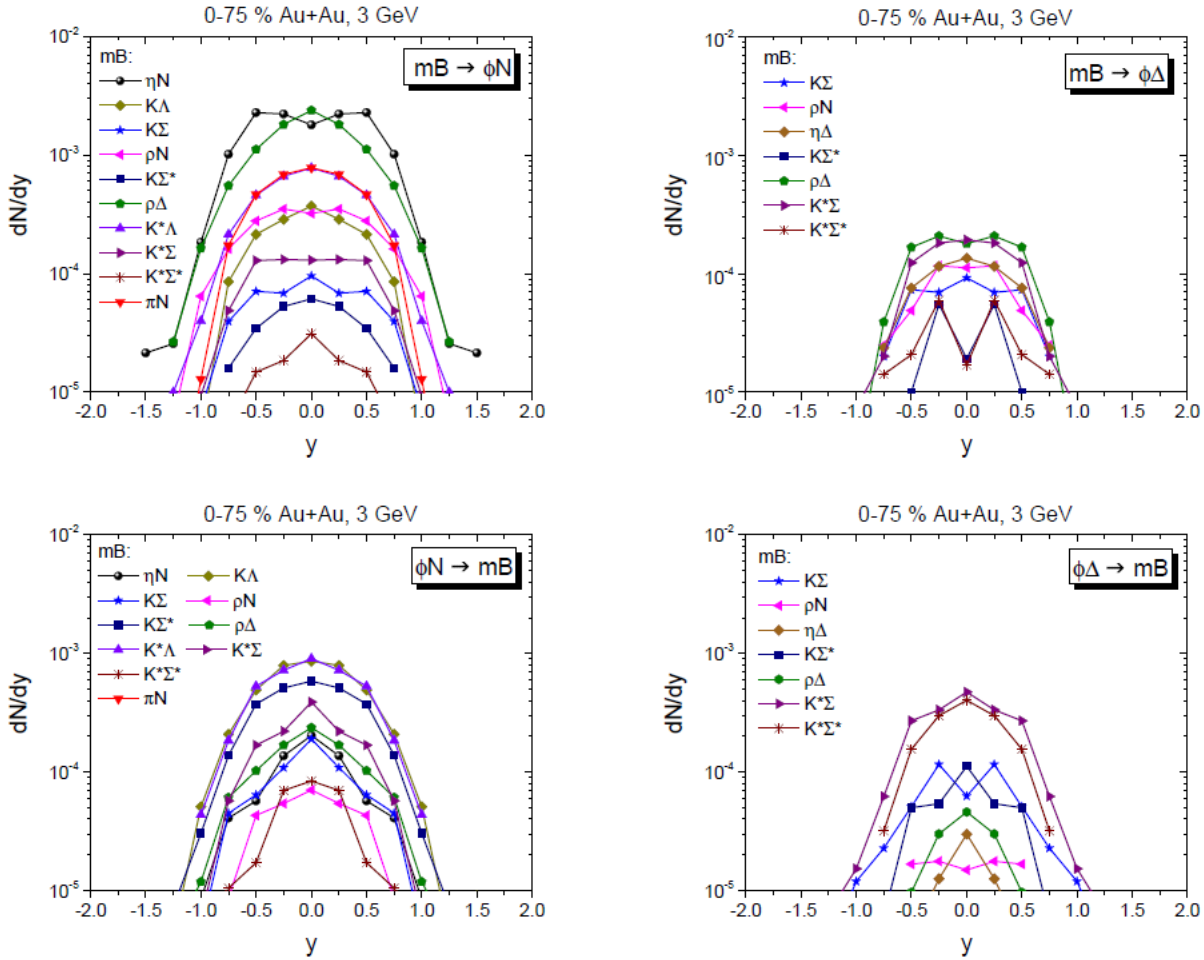


Scattering cross sections for Φ absorption are realized through the detailed balance

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

production

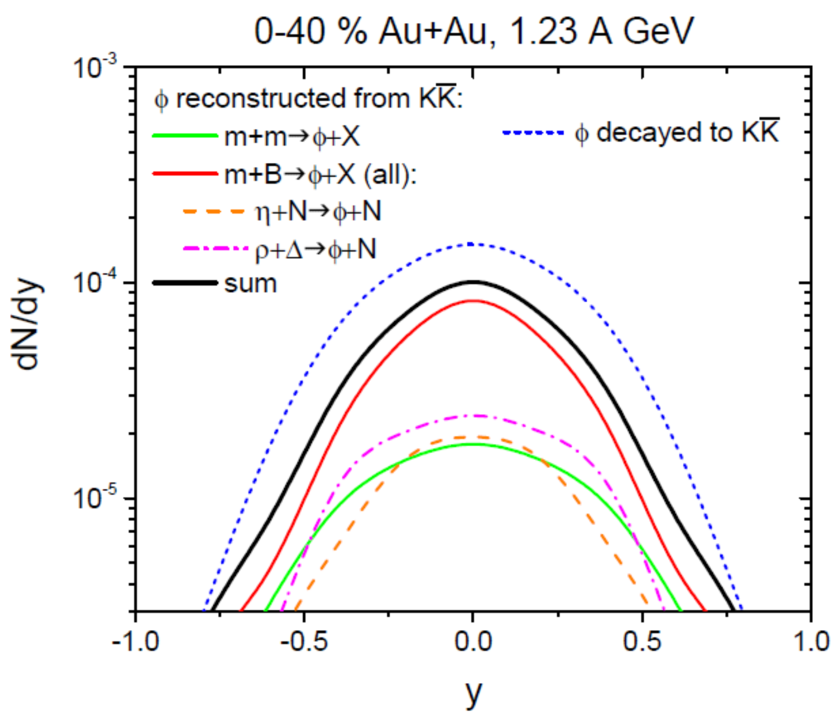
absorption

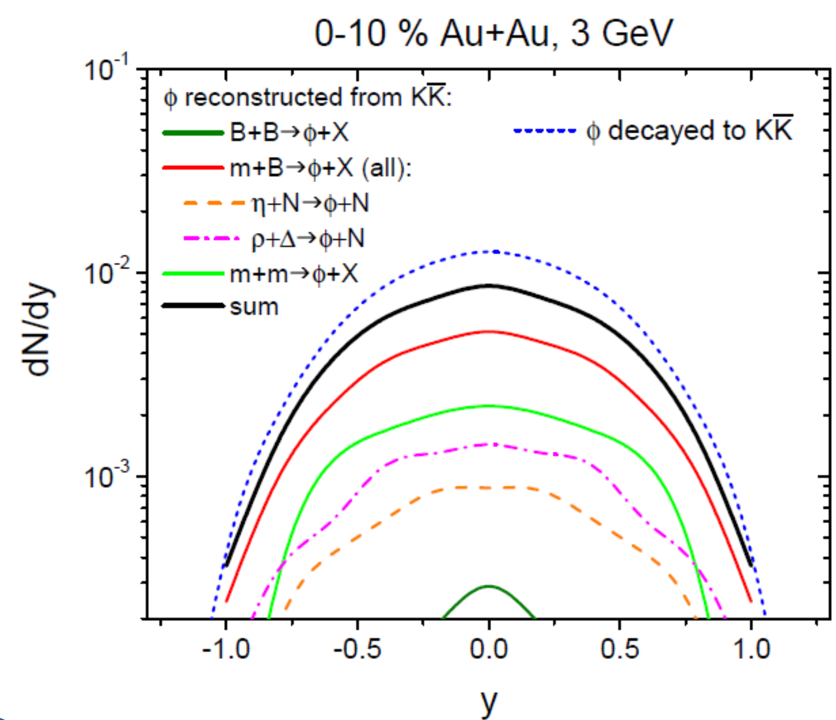


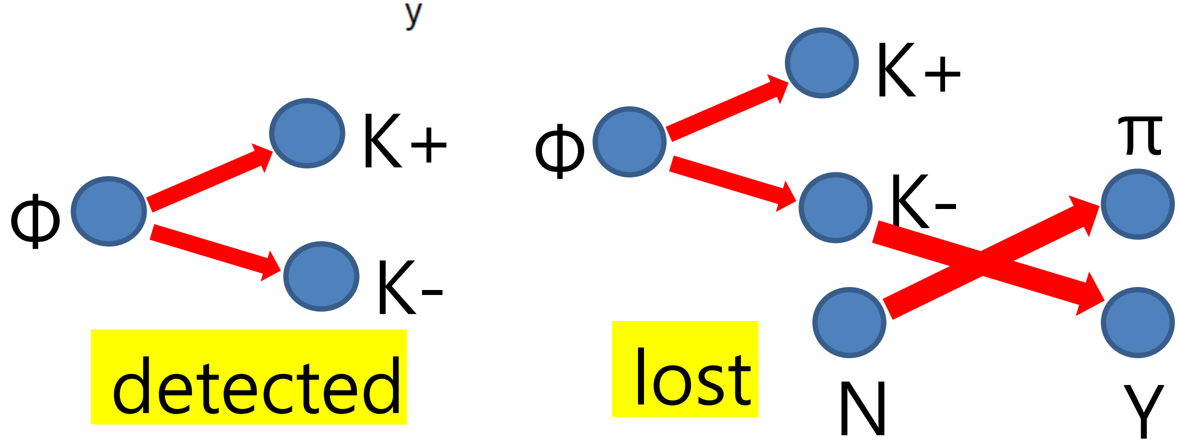
Most dominant production channels are η+N→Φ+N / ρ+Δ→Φ+N

4. Φ meson production in A+A collisions

Reconstructed Φ meson as a function of rapidity

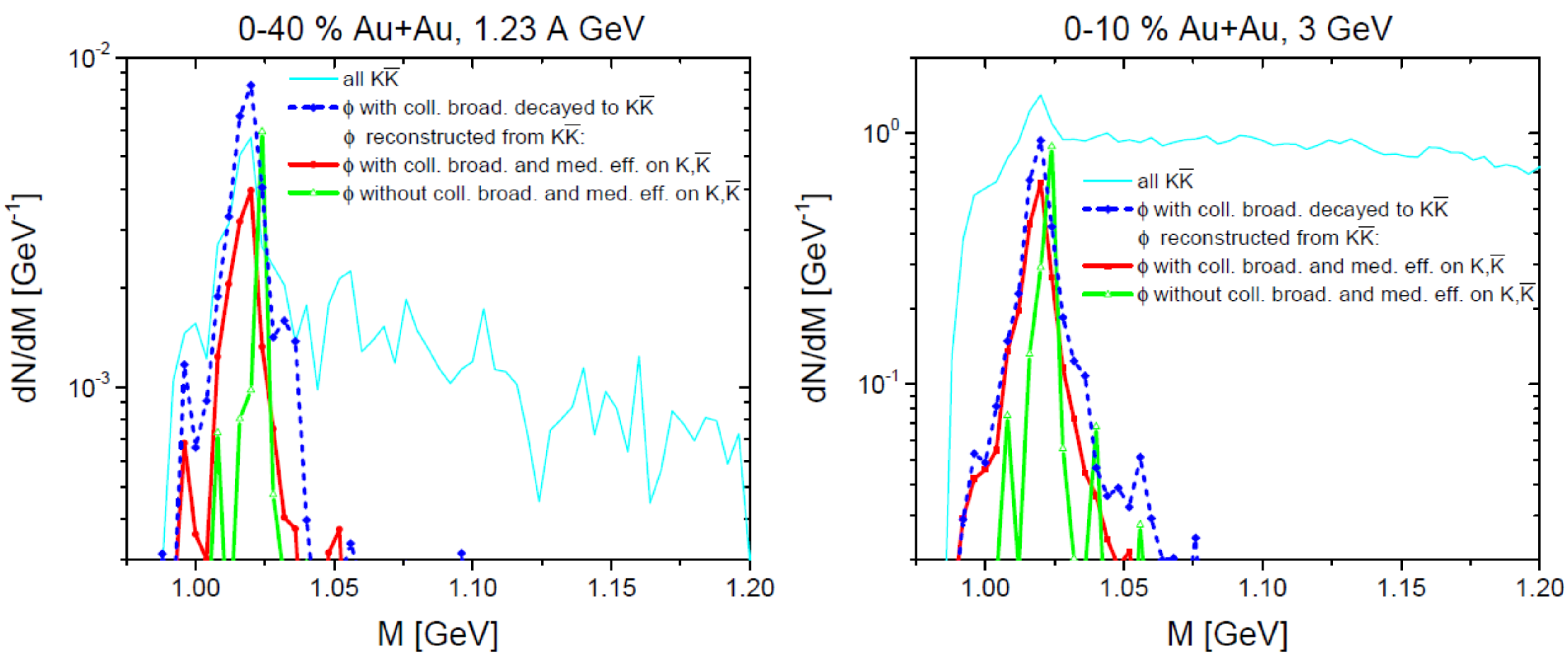






About 30-40 % of Φ are lost by secondary inelastic scattering

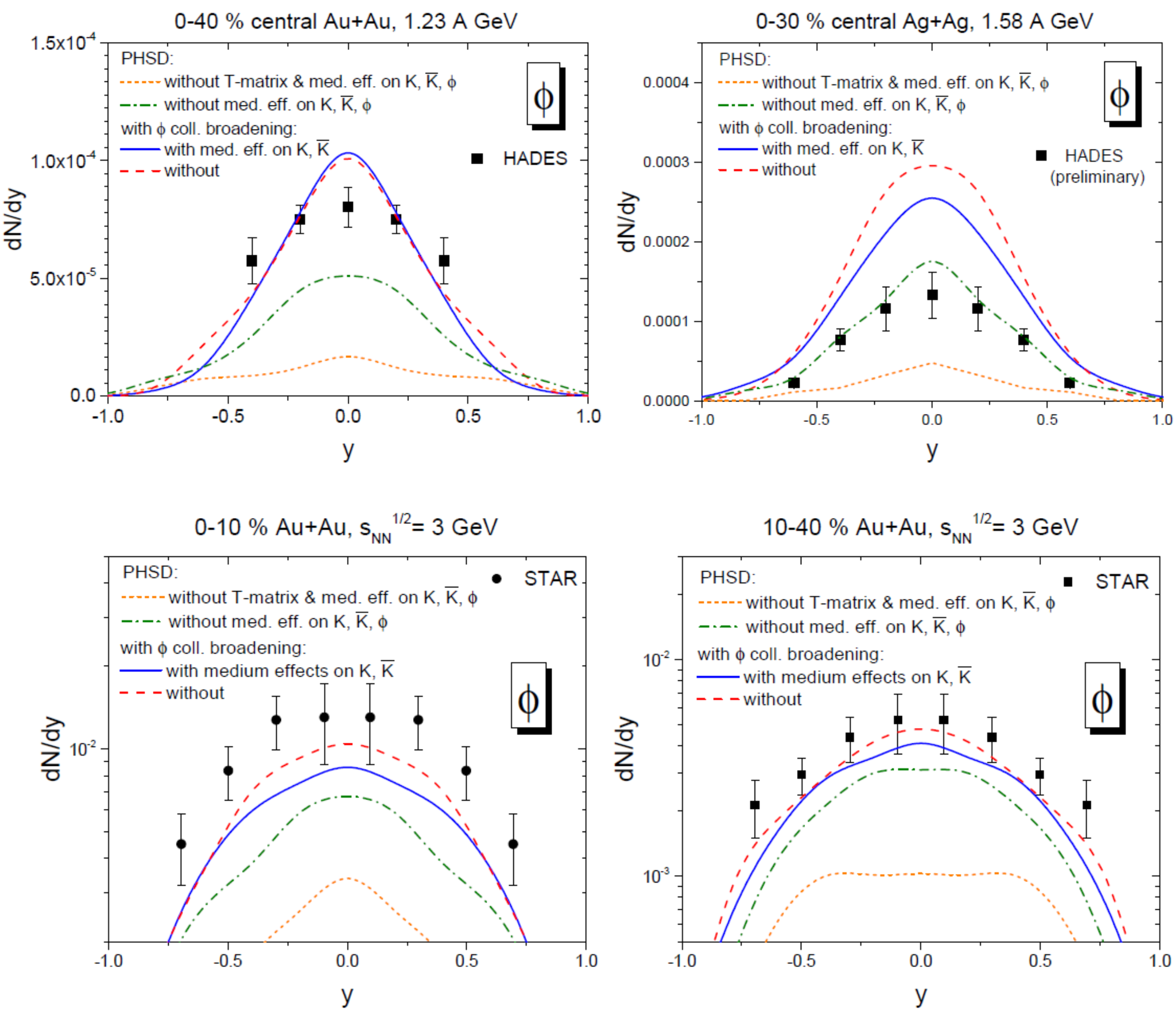
Reconstructed Φ meson as a function of invariant mass



Difference between **Red** & **Blue**: lost Φ meson due to rescattering

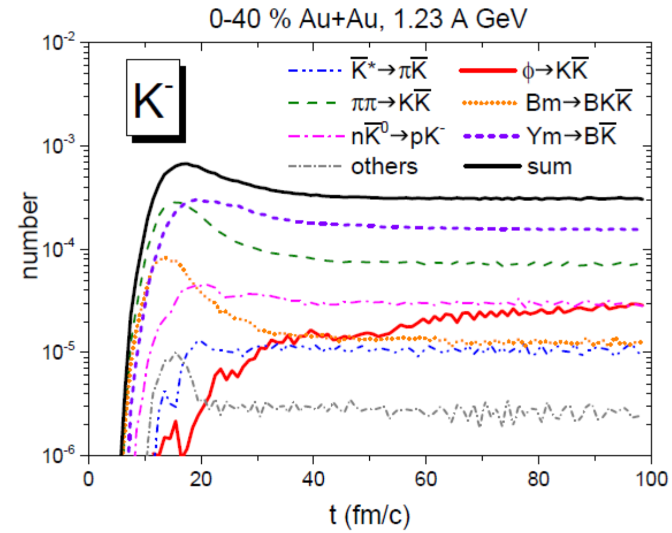
Difference between **Red** & **Green**: with/without width broadening

Comparison with experimental data

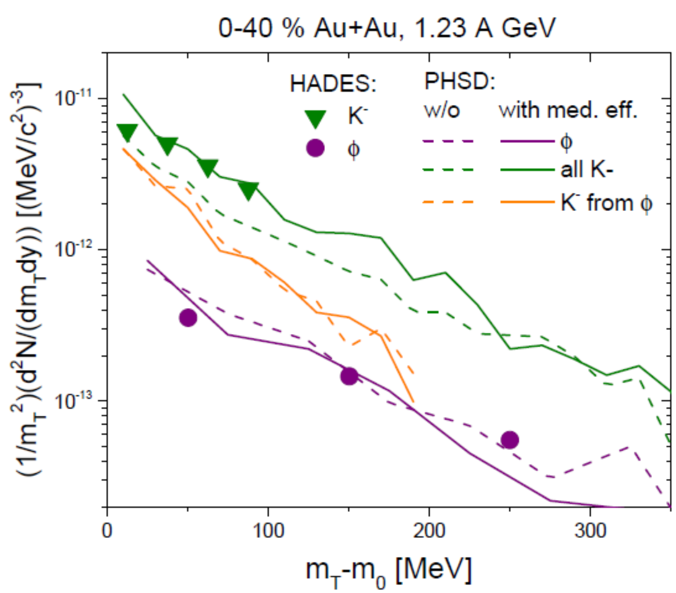


Orange: without T-matrix, width broadening
Green: with T-matrix but without width broadening
Red: with T-matrix, width broadening but without Med. Eff. on K, Kbar
Blue: all included

Effects of Φ production on K & Kbar

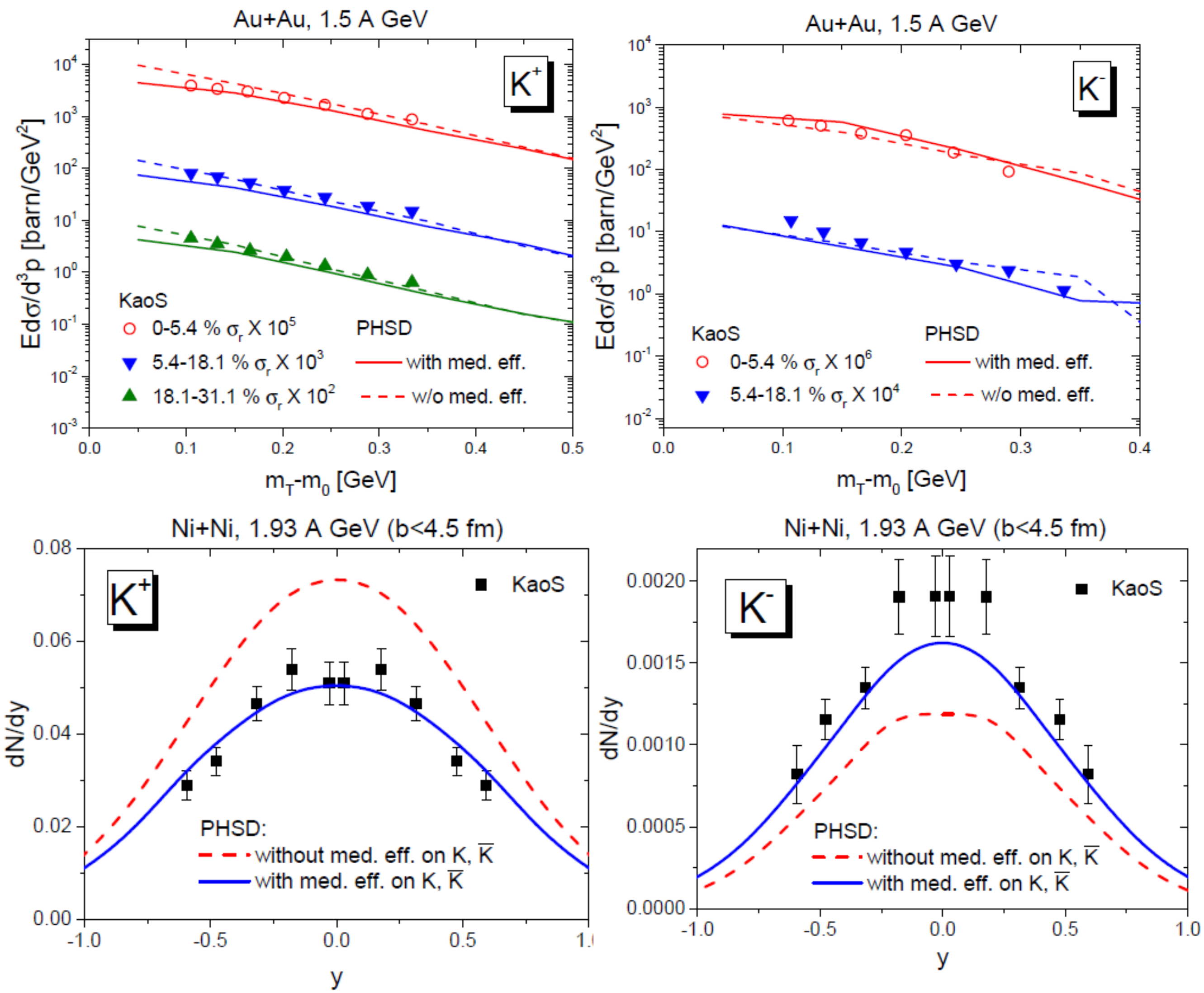


- Since Br (Φ→K^+K^-)~49 %, Φ production affects especially K^-.
- About 20 % of Φ meson do not decay till t=100 fm/c.



- The spectrum of K^- from Φ decay **(orange)** is softer than that of all K^-.
- One possible explanation for the softening of K^-. However, …

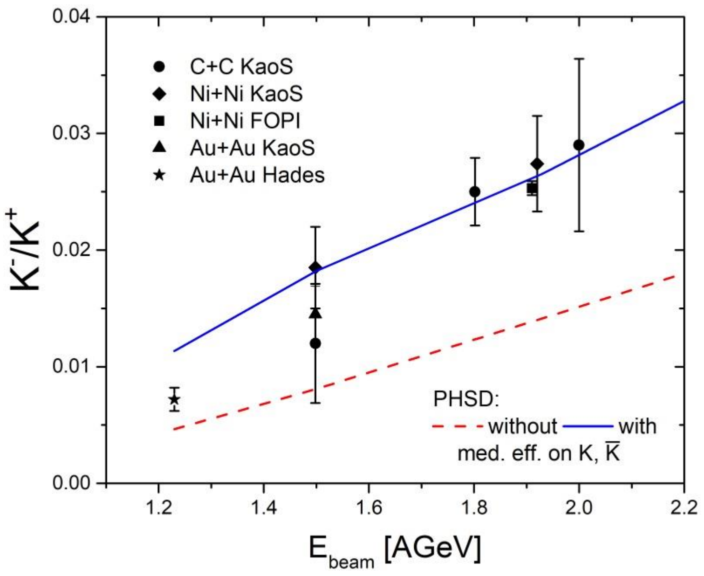
However, we still need Med. Eff. on K and Kbar to explain experimental data



Medium effects suppress K+ production and harden its spectrum.
On the contrary, they enhance K- production and soften its spectrum

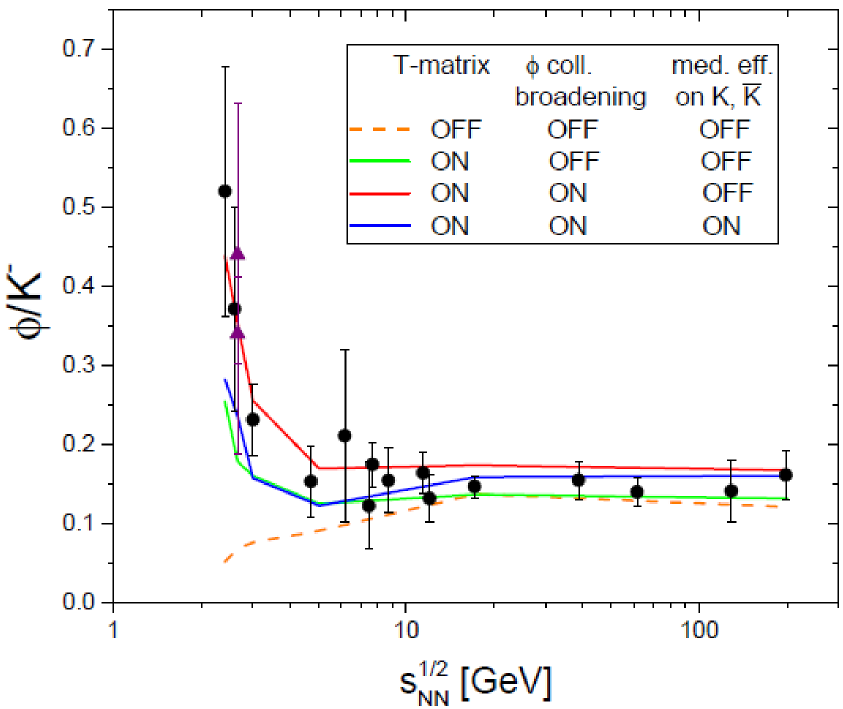
Song,PRC103 (2021) 4, 044901; arXiv:2205.10251

K^-/K^+ ratio



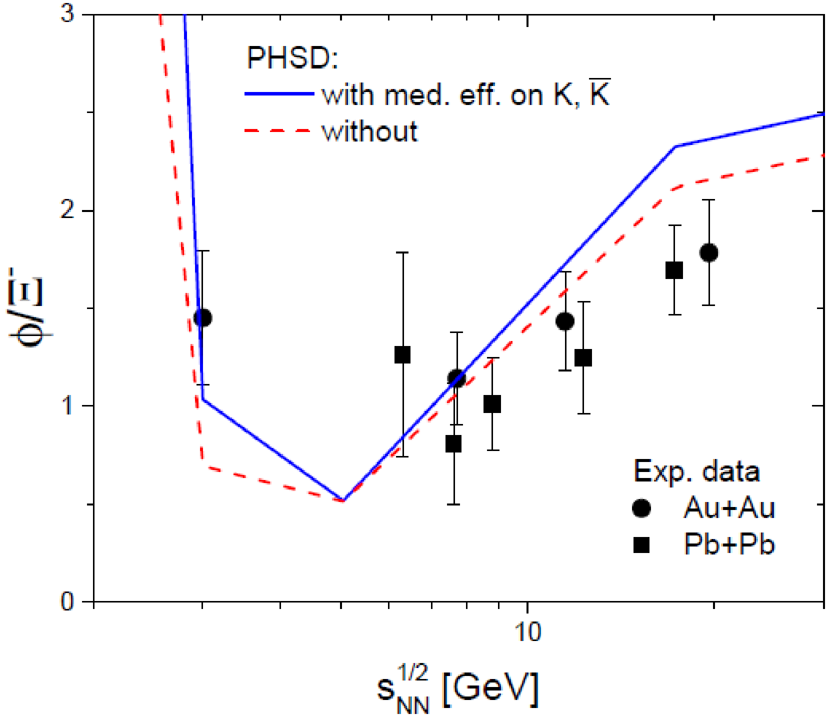
- Med. Eff. on K & Kbar are necessary to explain K^-/K^+ ratio, since they enhance K^- and suppress K^+

Φ/K⁻ ratio



- **Orange:** without T-matrix & Φ broadening underestimate the ratio at low energies
- T-matrix (**green**), T-matrix & Φ broadening (**red**) enhance the ratio
- However, Med. Eff. on K, Kbar (**blue**) suppress it due to the enhanced K^- production
- At high energies the ratio is less sensitive, because dominant process for Φ production is hadronization

Φ/Ξ⁻ ratio



- Med. Eff. on K & Kbar do not affect the ratio.
- Both are consistent with Exp. Data.

5. Summary

- We have investigated the hidden (and open) strangeness production in heavy-ion collisions from subthreshold to very high energies within Parton-Hadron-String Dynamics (PHSD) transport approach with off-shell propagation based on Kadanoff-Baym Eq.
- We can explain the experimental data on Φ production in heavy-ion collisions, if

1. more production channels from meson+baryon scattering are included, based on T-matrix calculations from SU(3) effective Chiral Lagrangian,
2. and are introduced the collisional broadening of Φ meson width in nuclear medium
3. as well as the medium effects on kaon and anti-kaon.

Thank you for your attention!