In-medium effects in ϕ meson production in heavy-ion collisions from subthreshold to relativistic energies

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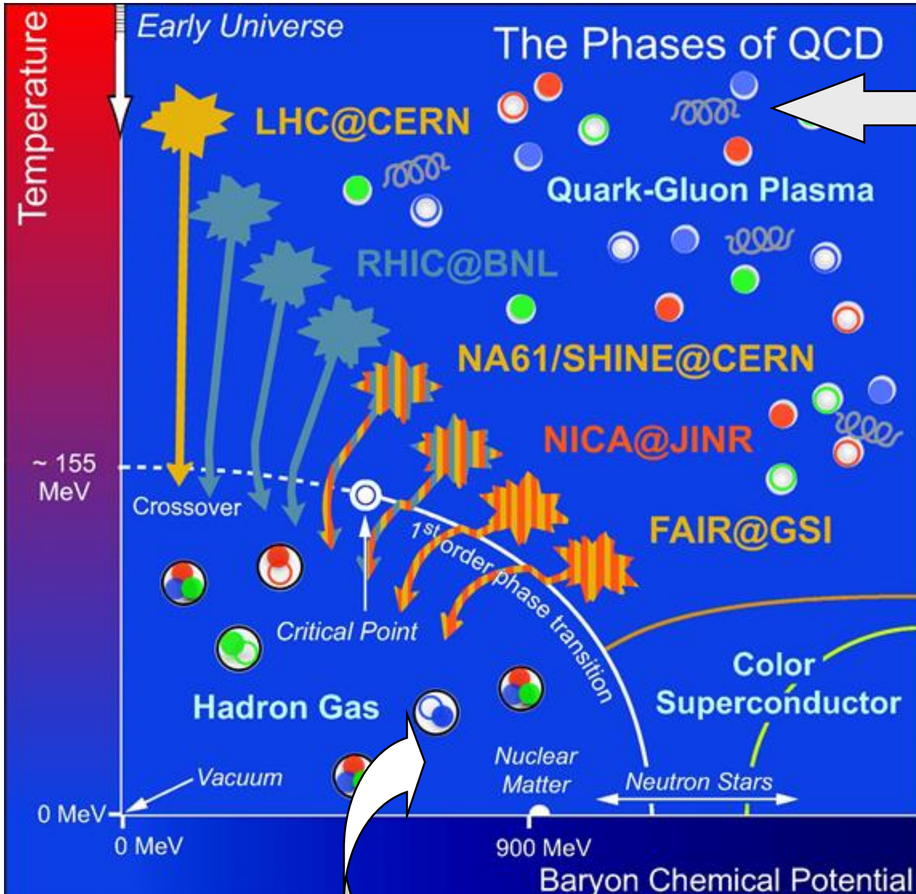
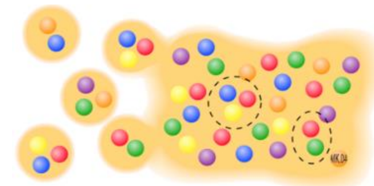
XVI edition of the Workshop on Particle Correlations and Femtoscopy and the IV edition of the Resonance Workshop
Catania, Italy, 6-10 November 2023

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

In-medium effects

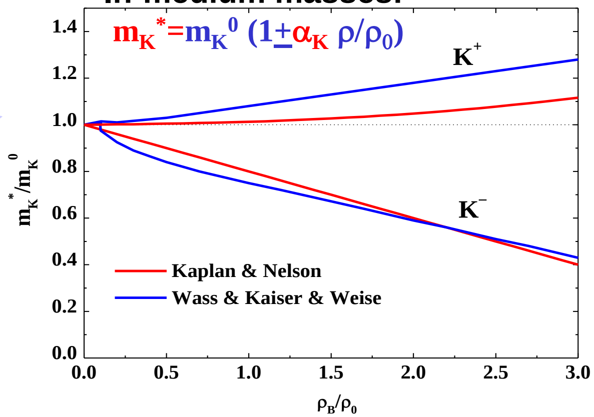
The hadrons - in particular vector mesons (ρ,ω,ϕ) and strange mesons (K, Kbar and K*) - modify their properties in the dense and hot nuclear medium due to the strong interaction with the environment

Models:

- **chiral SU(3) model, chiral perturbation theory, relativistic mean-field models: KN-potential ➔ ‚dropping' of K^- mass and ‚enhancement' of K^+ mass, collisional broadening of vector meson spectral functions**

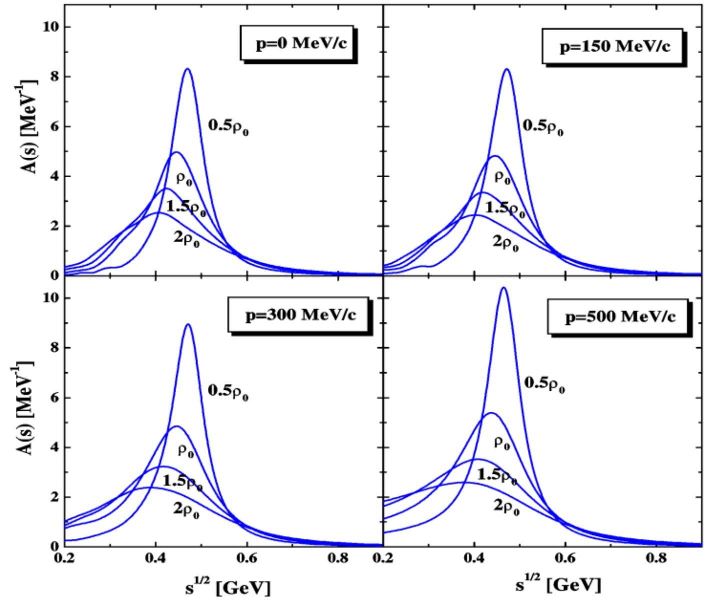
Kaplan and Nelson, PLB 175 (1986) 57;
Weise, Brown, Schaffner, Krippa, Oset, Lutz, Mishra, ... et al.

In-medium masses:



self-consistent coupled-channel approach
- G-matrix: Tolos et al., NPA 690 (2001) 547

➔ 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)

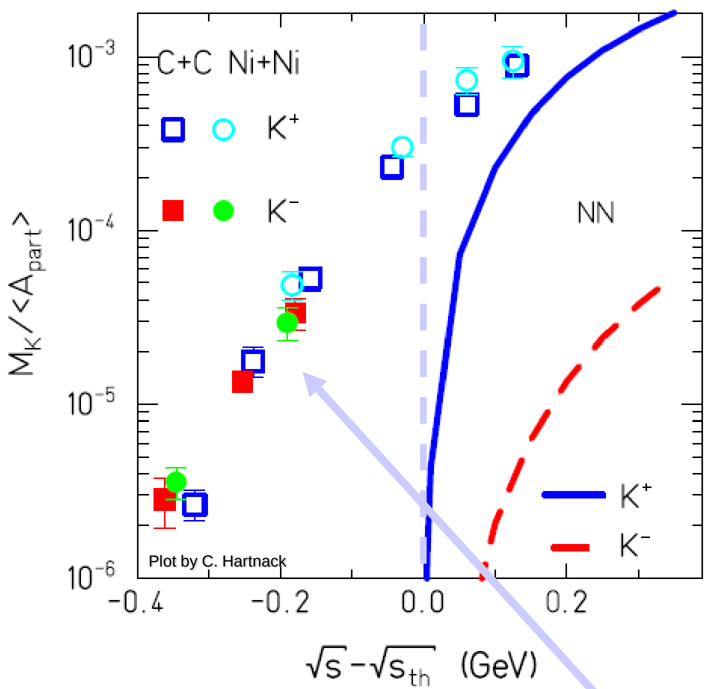


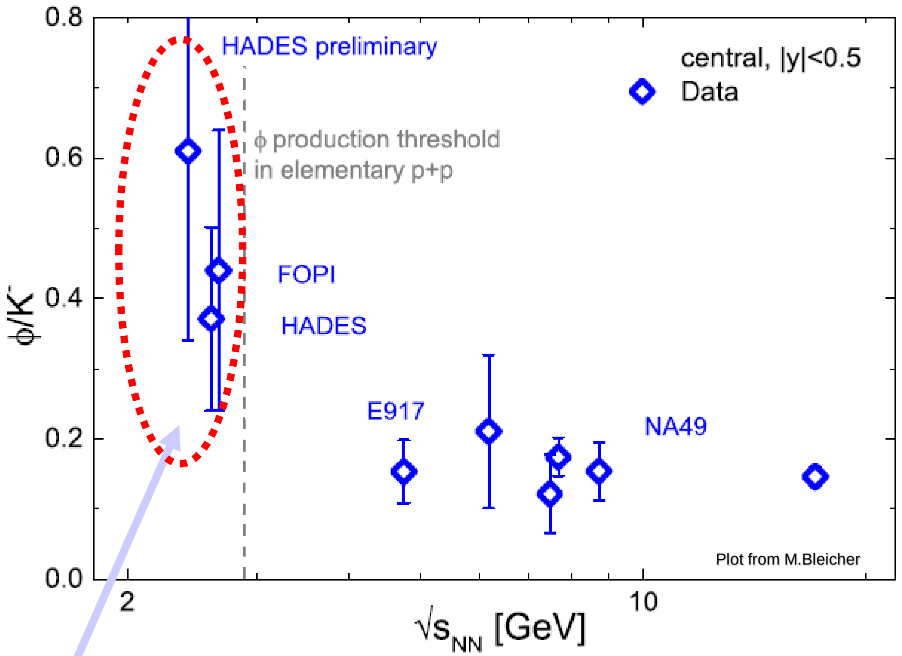
In PHSD: W. Cassing et al., NPA 727, 59 (2003)

Strangeness production in AA vs. NN

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

➔ **Study open and hidden strange meson (ϕ, K, Kbar) production in A+A at (sub-)threshold energies**





"enhanced" ϕ multiplicity?!

- **AA collisions:**
  experimental observation of K^+,K^- and ϕ production below the NN-threshold !

Subthreshold strangeness production in A+A vs NN

Subthreshold open and hidden strangeness production in A+A vs N+N :
- due to the Fermi motion
- production by secondary multi-step reactions and strangeness exchange reactions
- due to the in-medium effects – lowering/enhancing the strangeness production thresholds due to the mass reduction/enhancement

I. Strangeness production channels in A+A at low energies

- **baryon-baryon collisions:**

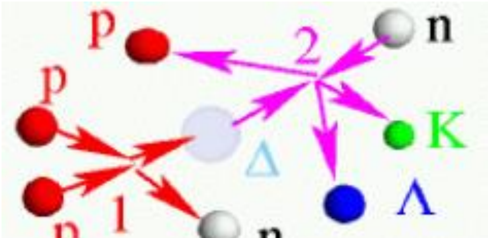
NN:

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

$K = (K^+, K^0)$
$\overline{K} = (K^-, \overline{K}^0)$
$B = (N, \Delta, \ldots)$
$Y = (\Lambda, \Sigma)$
$m = (\pi, \eta, \rho, \ldots)$

$K^+(u\bar{s}), K^0(d\bar{s})$,
$K^-(\bar{u}s), \overline{K}^0(\bar{d}s)$,
$\phi(s\bar{s})$,
$\Lambda(uds), \Sigma^0(uds)$
$\Sigma^+(uus), \Sigma^-(dds)$

multi-step reactions:



Plots by C. Hartnack

- **meson-baryon collisions:**

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

Coupled channels - strangeness exchange reactions for s-quark : dominant channel for low energy K^- production!

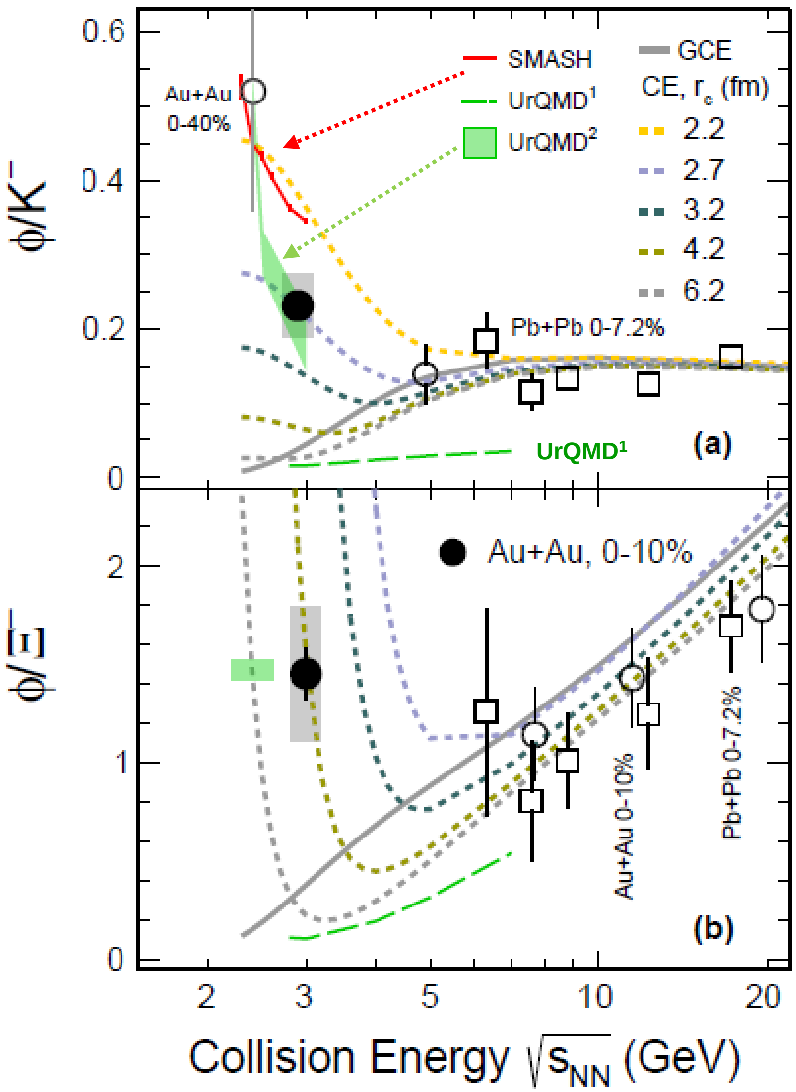
- **resonance decays:** $K^* \rightarrow \pi+K, \ldots,\ \phi \rightarrow K+\overline{K}$

- **meson-meson collisions:**

$$m+m \rightarrow K+\overline{K}$$
$$K+\overline{K} \rightarrow \phi$$

The production cross sections and self-energies of ϕ, K, $\overline{K}$ are modified in the nuclei medium !

ϕ/K^- ratio in A+A: theoretical models vs exp. data

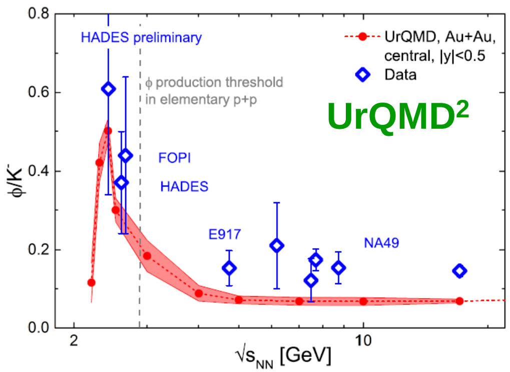


STAR, Phys.Lett.B 831 (2022) 137152

- **Statistical model:**
  GCE: doesn't describe exp. Data
  CE: description of ϕ/K^- with r_c~2.7fm and ϕ/Ξ^- with r_c~4.2fm, i.e. with different values of the strangeness correlation radius (r_c) which governs the canonical suppression: ϕ (hidden strangeness) is not suppressed, K^- - suppressed
  A. Andronic at al., Nature 561 (2018) 321

- **UrQMD[1]: standard**
  (consistent with early BUU study by H.W. Barz et al., NPA 705 (2002) 223 including $\rho R \rightarrow N\phi$ reactions)

- **UrQMD[2]: hypothetic N* decay to ϕ**
  Br(N*→N+ϕ)=0.2%
  - fixed to reproduce ANKE p+p→p+p+ϕ data
  J. Steinheimer, M. Bleicher, JPG 43 (2016) 015104



- **SMASH: hypothetic N* decay to ω, ϕ**
  Br(N*→N+ϕ)=0.5%
  V. Steinberg et al., PRC 99 (2019) 064908 (2019)

PHSD: towards a solution of the ϕ/K^- puzzle

Can we understand the observed "enhanced" ϕ multiplicity and ϕ/K^- ratio close to threshold without assuming the "hypothetic" (not observed) decay N* to ϕ mesons with unknown Br ratio, i.e. within a more conventional approach? How?

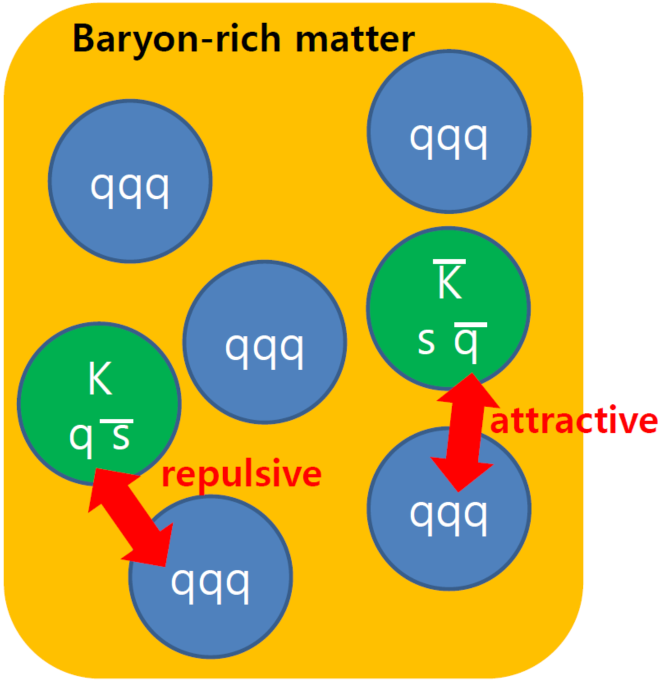
- **By incorporating the dynamical modifications of the ϕ meson and K^- properties in the medium such as a collisional broadening of the ϕ meson spectral function in a self-consistent coupled-channel approach - G-matrix for K^- properties**

- **By accounting for additional multistep meson-baryon and meson-hyperon reactions for ϕ meson production as predicted by the SU(6) extension of the meson-baryon chiral Lagrangian within a unitary coupled-channel *T* -matrix approach**

➔ realization:
Off-shell microscopic transport approach PHSD

First implementation of the G-matrix to the off-shell PHSD: W. Cassing et al., NPA 727, 59 (2003) ⟹ **T. Song et al., PRC 106, 024903 (2022); PRC 103, 044901 (2021)**

In-medium production:
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:

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

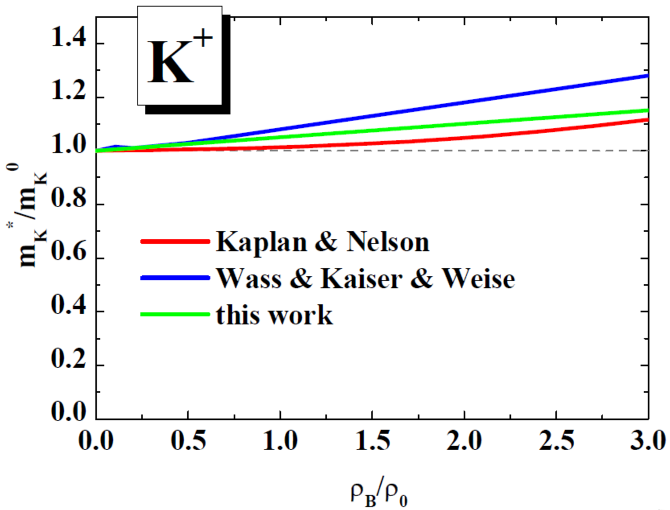
Single-particle energy of the kaon in nuclear matter is approximated in the nonrelativistic limit by

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

Repulsive potential V_K leads to **an increase of the effective kaon 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*)

Basic ideas:

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

* Improved!

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

Spin ½+ SU(3) baryon octet

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

$$\nabla_\mu B = \partial_\mu B + [\Gamma_\mu, B],$$

$$\Gamma_\mu = \frac{1}{2}(u^\dagger \partial_\mu u + u\, \partial_\mu u^\dagger),$$

$$U = u^2 = \exp(i\sqrt{2}\Phi/f),$$

$$u_\mu = i u^\dagger \partial_\mu U u^\dagger,$$

SU(3) pseudo-scalar meson octet

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

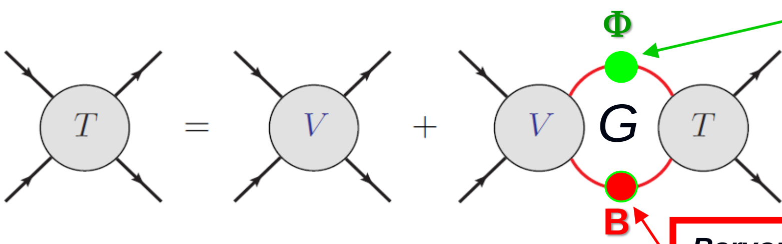
1) 1st G-matrix (based on the Jülich meson-exchange model): L. Tolos et al., NPA 690 (2001) 547
   → In first off-Shell PHSD study of strangeness: W. Cassing et al., NPA 727, 59 (2003)

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:



Meson selfenergy and spectral function

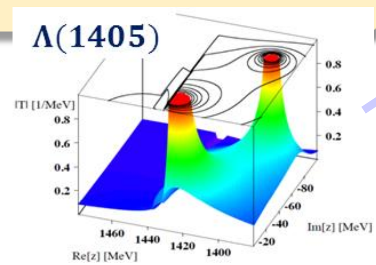
Baryons: Pauli blocking and potential dressing

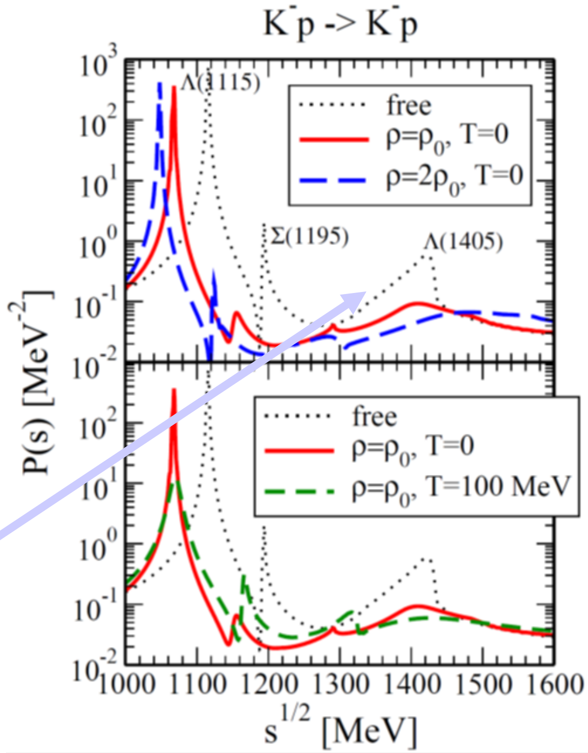
$$\mathcal{T}_{ij}(\rho,T) = V_{ij} + V_{il}\; G_l(\rho,T)\; \mathcal{T}_{lj}(\rho,T)$$

$$P \propto |T|^2$$

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

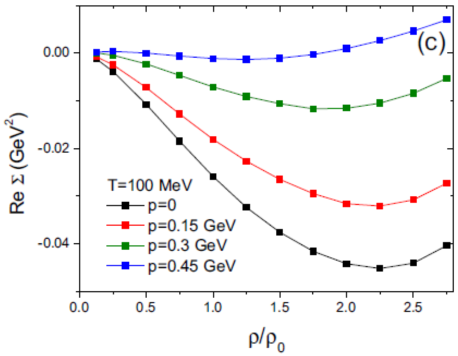
Off-shell antikaons properties and interactions

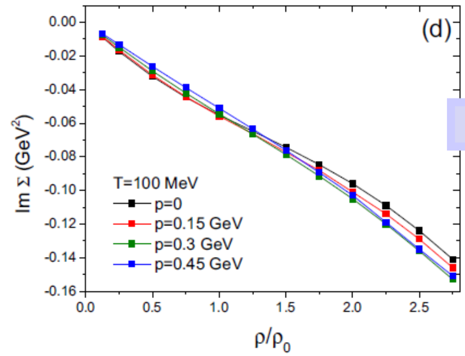
D. Cabrera et al., PRC 90 (2014) 055207

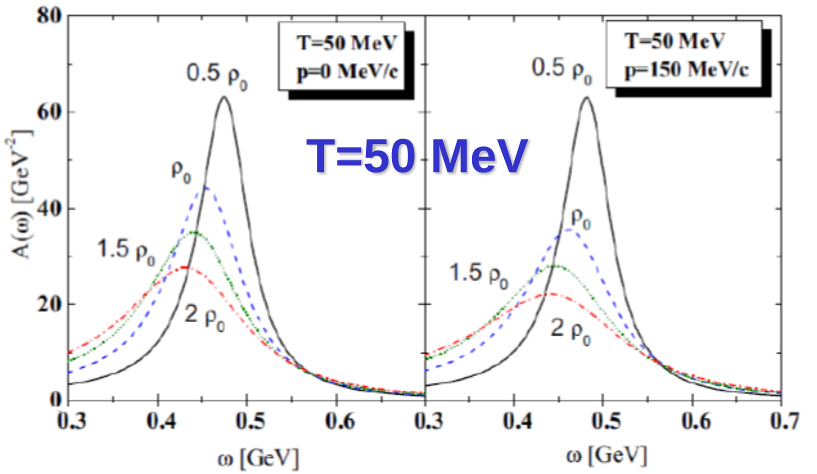
- **Spectral function of K^- within the G-matrix approach:**

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

Real & imaginary self- energies:

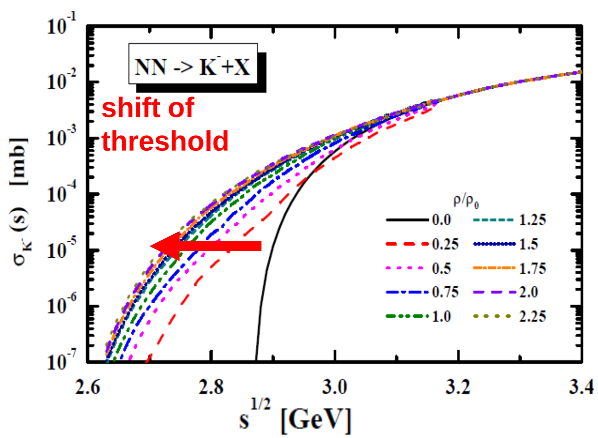


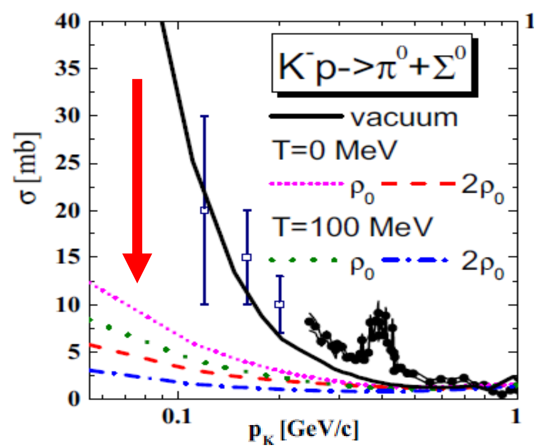




- **In-medium cross sections for K^- production and absorption are strongly modified in the medium**

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





➔ **enhanced K^- subthreshold production**

➔ **decrease of K^- absorption**

In-medium production of hidden strangeness - ϕ meson :

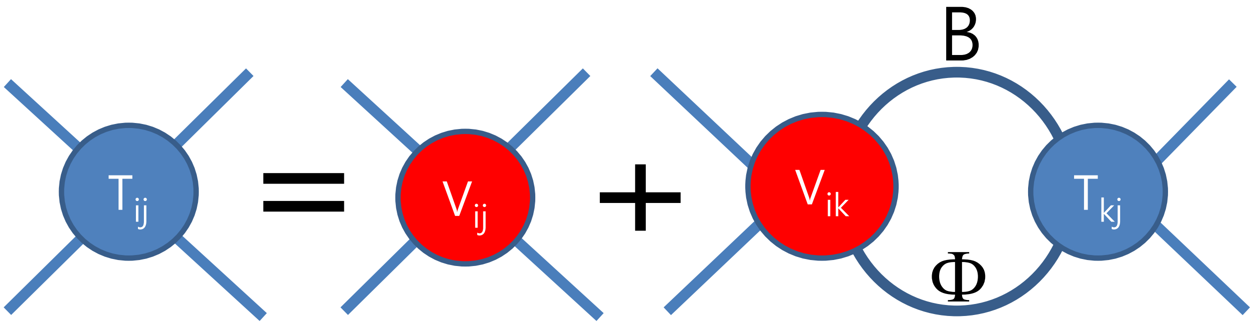
SU(6) chiral effective Lagrangian model + collisional broadening

SU(6) chiral effective Lagrangian model

- **Self-consistent unitarization**

SU(6) Chiral Lagrangian

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



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

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

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

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

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

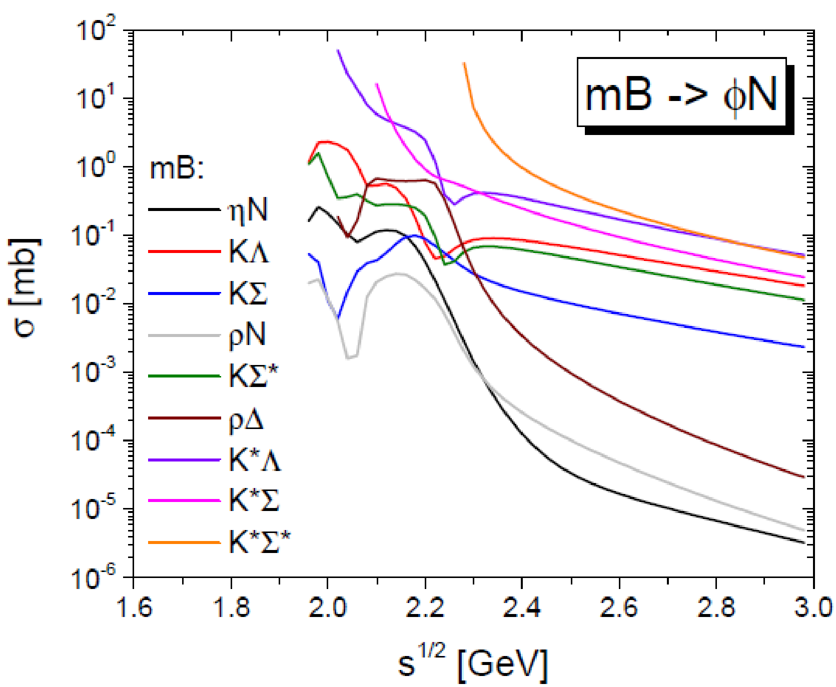
Tolos et al., NPA 690 (2001) 547

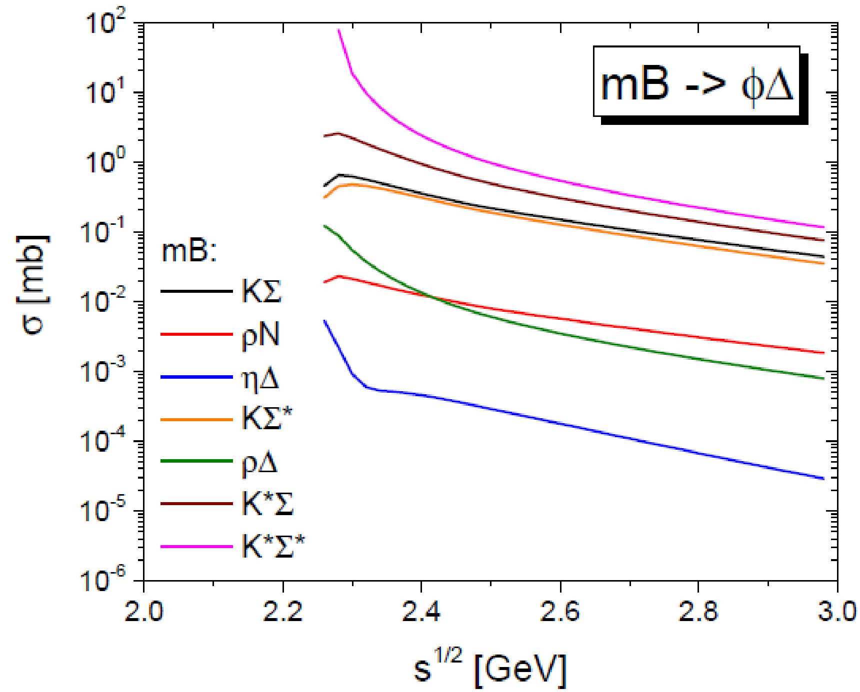
Cabrera et al., PRC 95, 015201 (2017)

Novel ϕ production channels within the SU(6) chiral model

1) mB scattering cross sections for ϕ production (m+B→ϕ+B)

Cabrera et al., PRC 95, 015201 (2017)





2) scattering cross sections for ϕ absorption (ϕ+B→m+B) are realized through detailed balance

In-medium properties and production of ϕ mesons

- **In-medium spectral function of ϕ within collisional broadening scenario:**

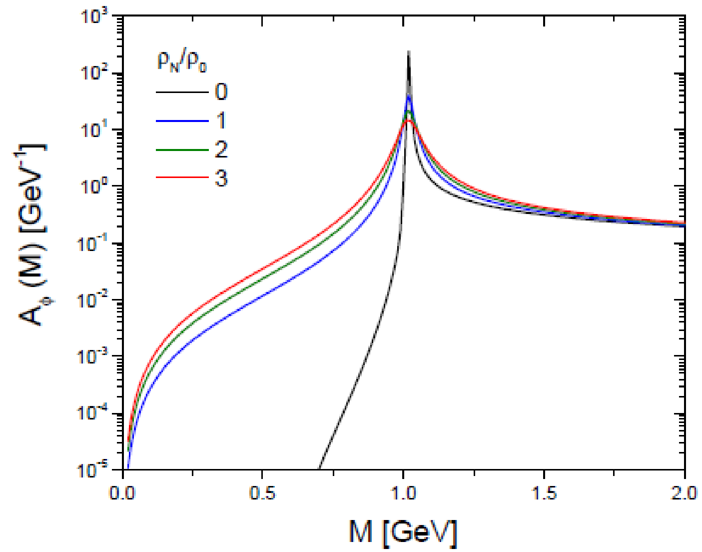
$$\Gamma^*_V(M,|\vec{p}|,\rho_N) = \Gamma_V(M) + \Gamma_{coll}(M,|\vec{p}|,\rho_N).$$

- **Collisional width**

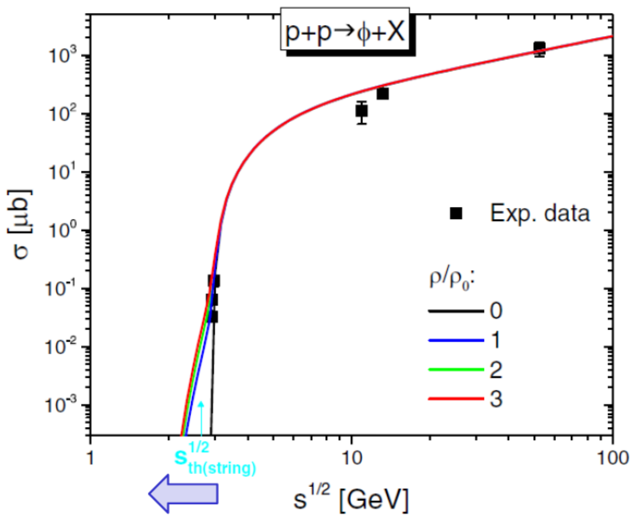
$$\Gamma_{coll}(M,|\vec{p}|,\rho_N) = \gamma\ \rho_N < v\ \sigma^{tot}_{VN} > \approx \alpha_{coll}\frac{\rho_N}{\rho_0}$$

25 MeV from

Muto et al., PRL 98, 042501 (2007)
Gubler et al., NPA 954, 125 (2016)
Cabrera et al., PRC 95, 015201 (2017)
Kim et al., PRD 105, 114053 (2022)



- **In-medium ϕ production cross sections with accounting for a spectral function:**



In-medium effect:
shift of threshold to smaller $s^{1/2}$

➔ enhanced ϕ subthreshold production in a dense medium

T. Song et al., PRC 106, 24903 (2022)

Dynamical description of in-medium effects:

Off-shell transport theory for strongly interacting systems

Transport description of strongly interacting systems

In-medium effects (on hadronic or partonic levels!) = changes of particle properties in the hot and dense medium

Examples: **hadronic medium** - vector mesons, strange mesons, baryons
QGP – dressing of partons

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?**

❑ **semi-classical BUU**

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

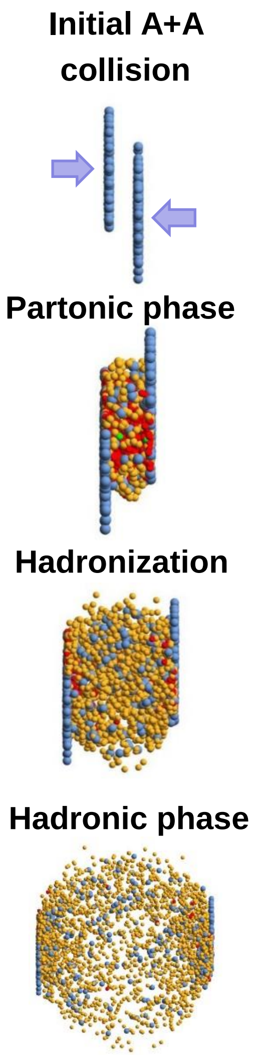
❑ **generalized transport equations = off-shell transport approach!**

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

PHSD

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 $n \leftrightarrow m$ selected reactions (for strangeness, anti-baryons, deuteron production) - applied here for strangeness production:
  B+B↔B+Y+K,   B+m↔B+K+Kbar

- **QGP:**
  strongly interacting quasiparticles (quarks and gluons) with dynamical temperature and density dependent spectral functions

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

(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 $i = 1, 2, 3$.

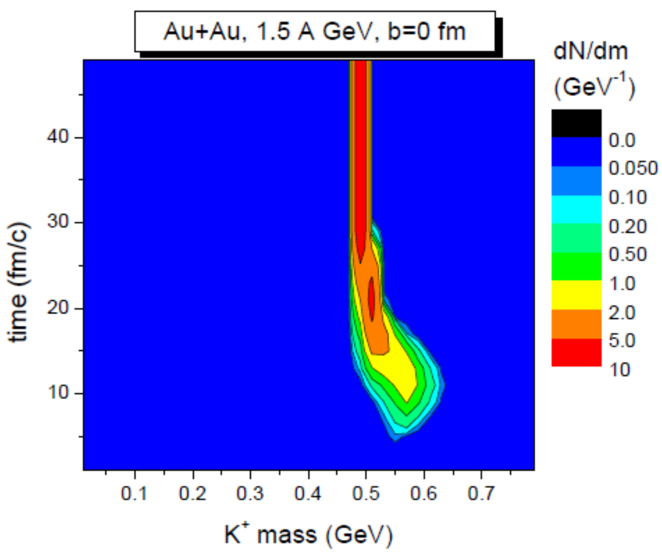
Equivalent in the limit ImΣ, ∇pReΣ →0

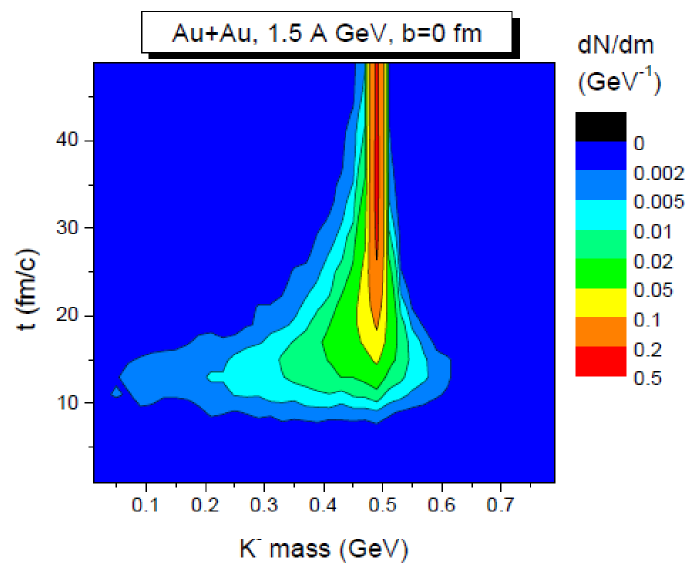
Off-shell propagation for antikaon within generalized Cassing-Juchem EoM based on Kadanoff-Baym Equations

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

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

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





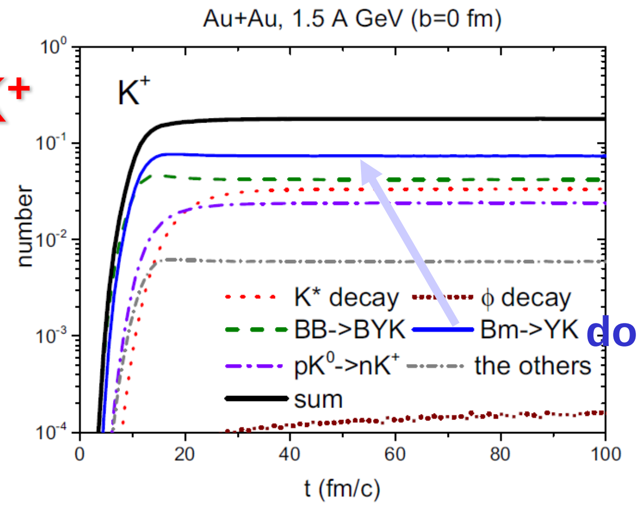
W. Cassing , S. Juchem, NPA 665 (2000) 377; 672 (2000) 417; 677 (2000) 445

Dynamics of open and hidden strangeness at SIS - BES STAR energies

Time evolution of ϕ, K^+, K^- production in Au+Au

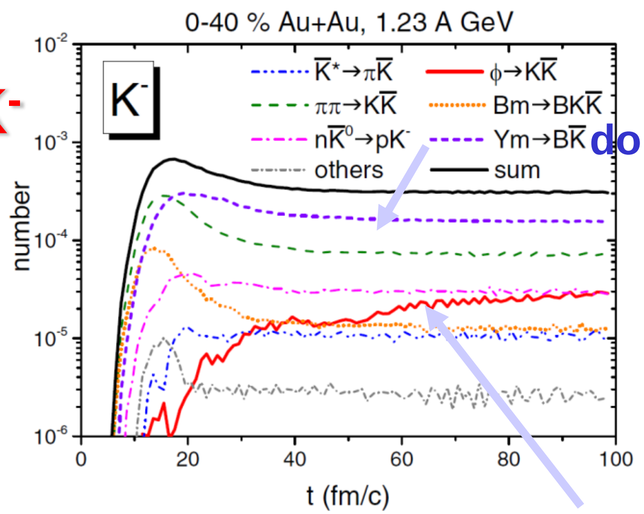
Channel decomposition of the K+, K- production vs. time

K^+



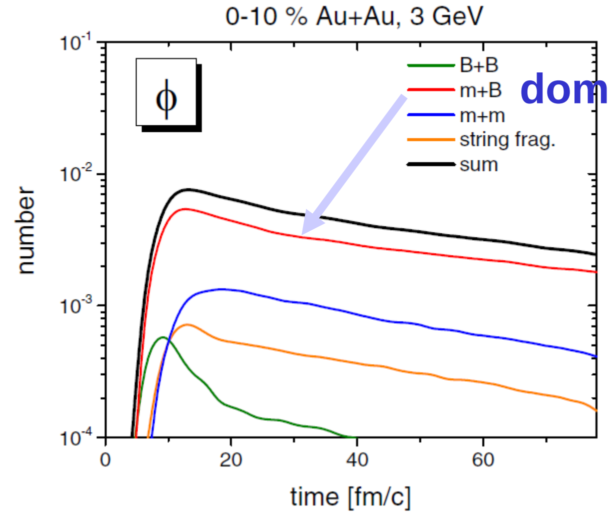
dominant

K^-

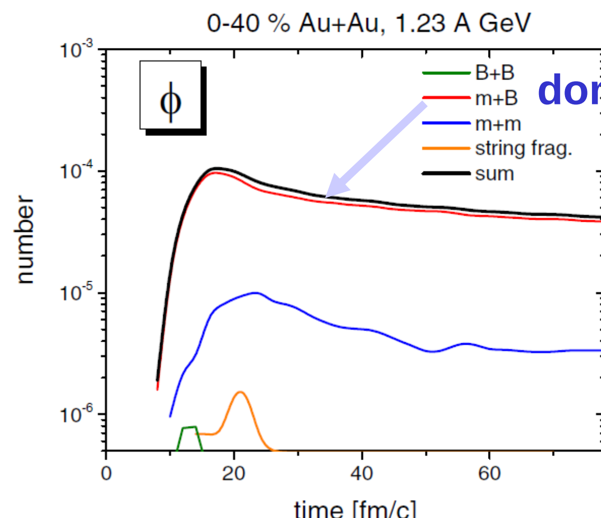


dominant

Channel decomposition of the ϕ production vs. time



dominant



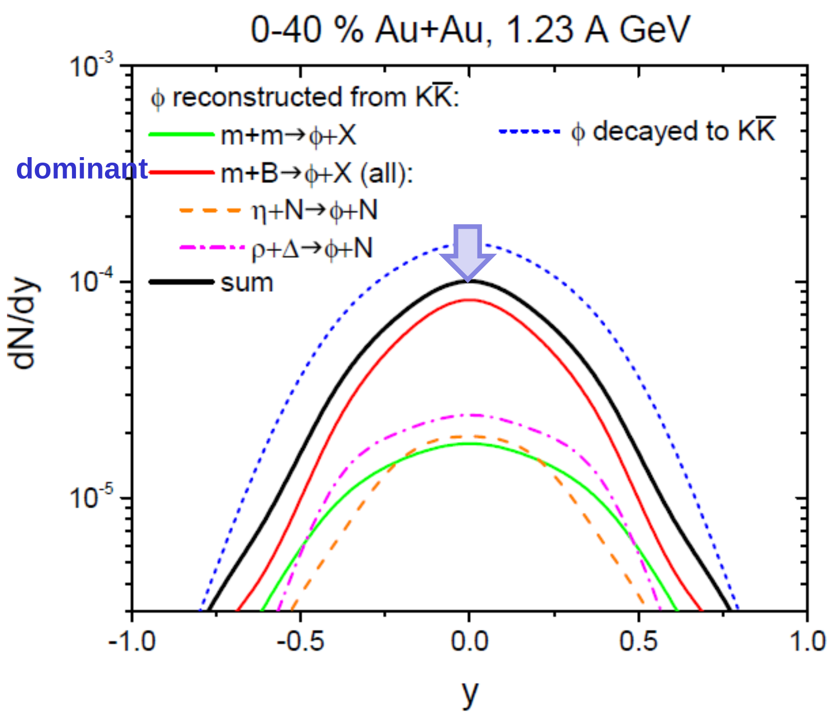
dominant

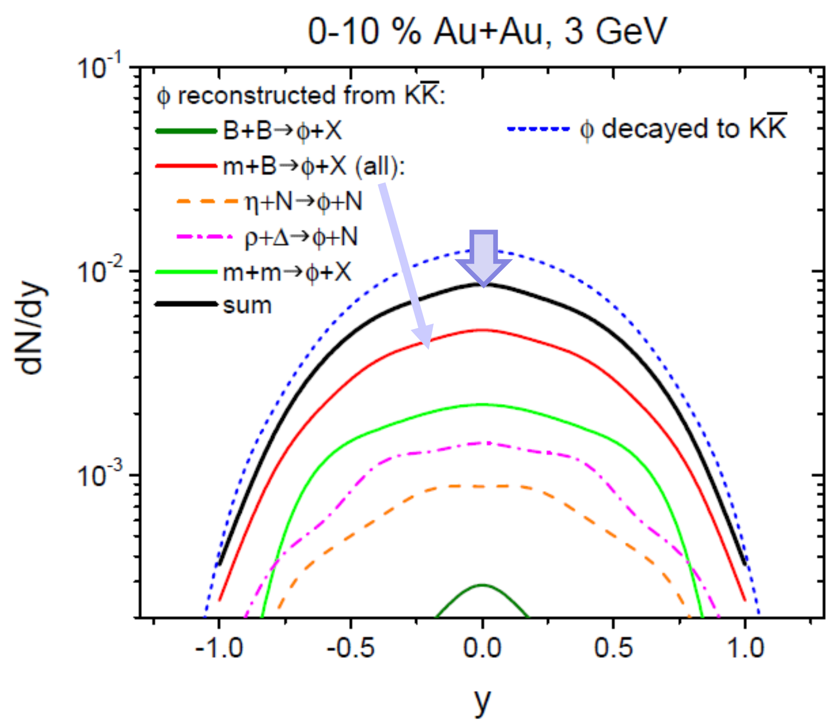
Small contribution from ϕ decay to K^- production

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

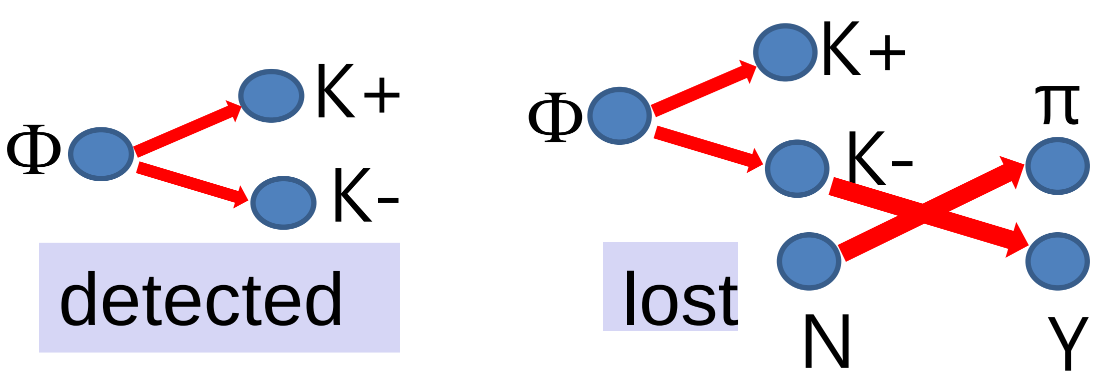
T. Song et al., PRC 106, 24903 (2022)

Channel decomposition of ϕ production vs. rapidity





➔ **The number of reconstructed ϕ from K+K− pairs, divided by Br(ϕ→K+K−), is smaller than the number of 'true' ϕ decaying to K+K-**



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

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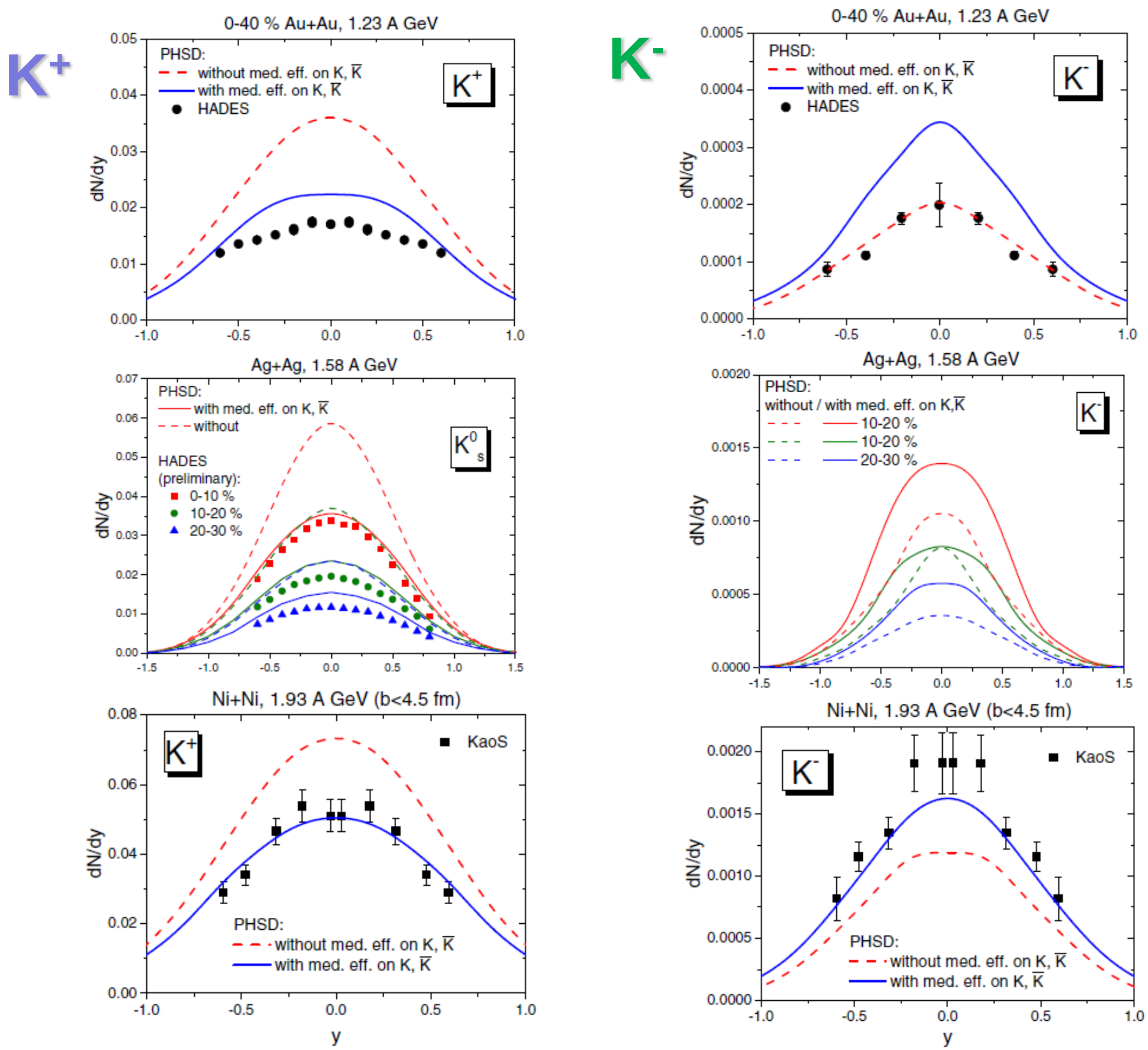
Rapidity distributions of (anti)kaons at SIS energies



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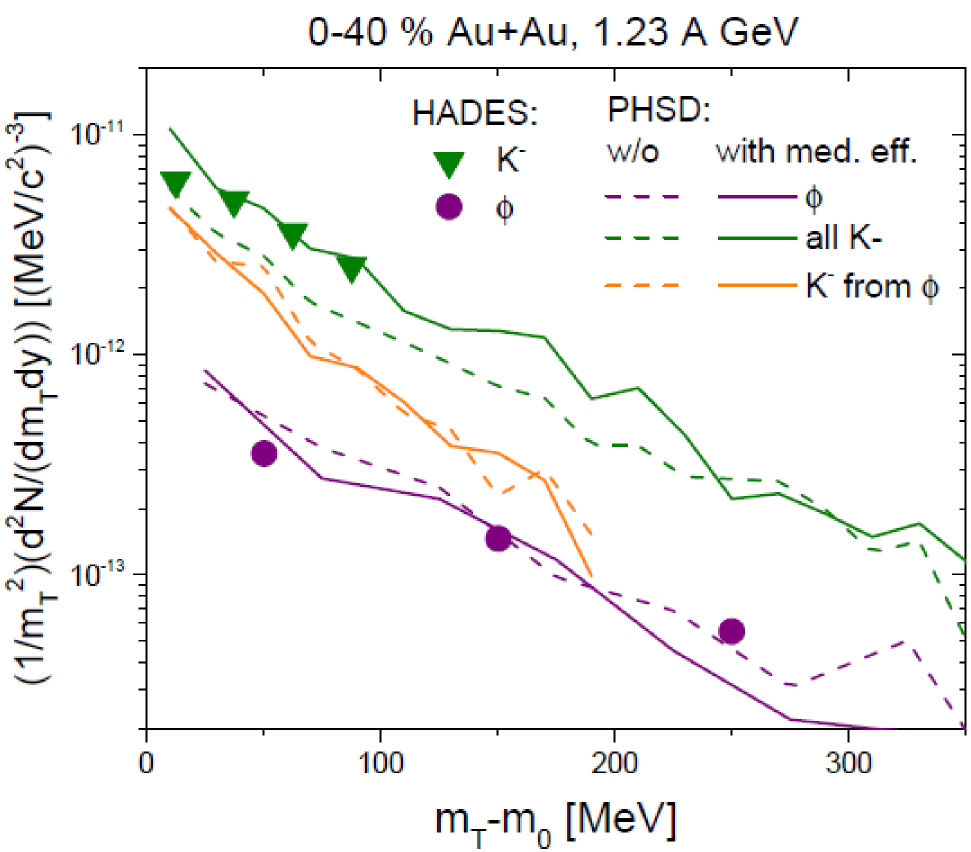
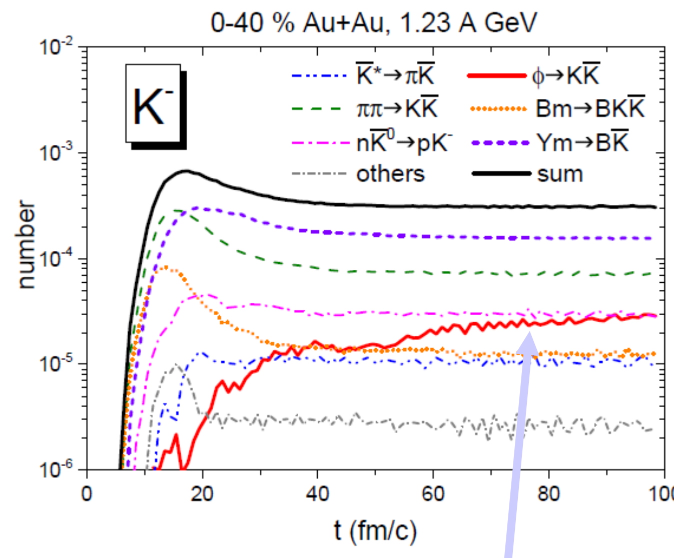
- **Good agreement with HADES and KaoS data for K+ and K- for semi-heavy systems**
- **Tension with HADES data for K^- for Au+Au at 1.23 A GeV**

- **In-medium effects suppress kaon production**
- **In-medium effects enhance antikaon production**

Effects of ϕ on (anti)K production at SIS energies





PHSD: small contribution from ϕ decay to K^- production

- **The m_T spectrum of K^- from ϕ decay (orange) is softer than that of all K^-, however, the relative contribution of K^- from ϕ decay is subdominant**
  ➔ can not affect much the total slope of K^-

- **➔ we need medium effects on K and Kbar to explain various experimental data consistently**

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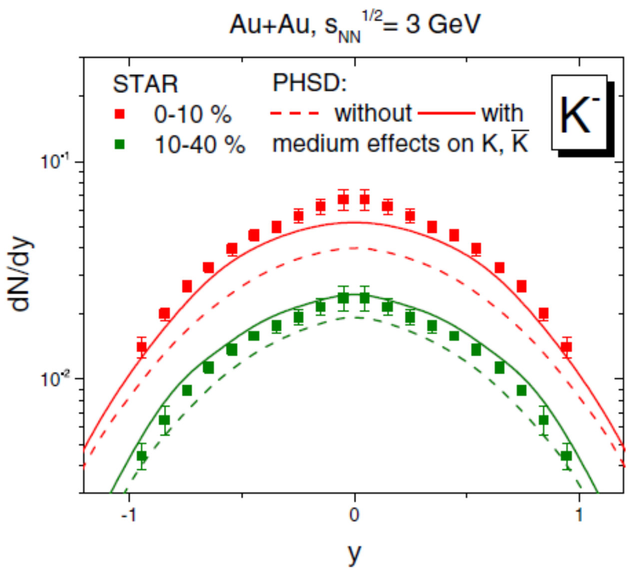
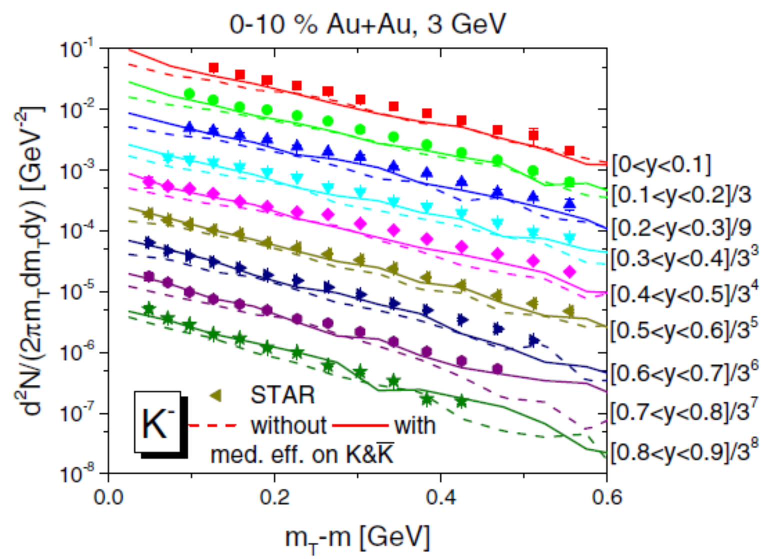
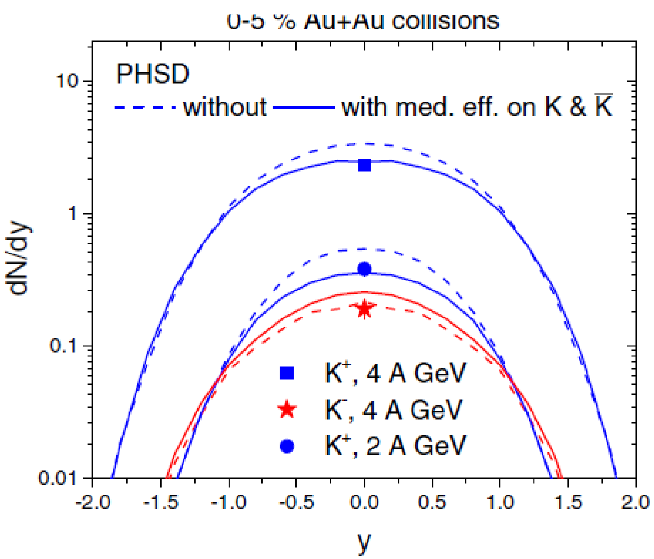
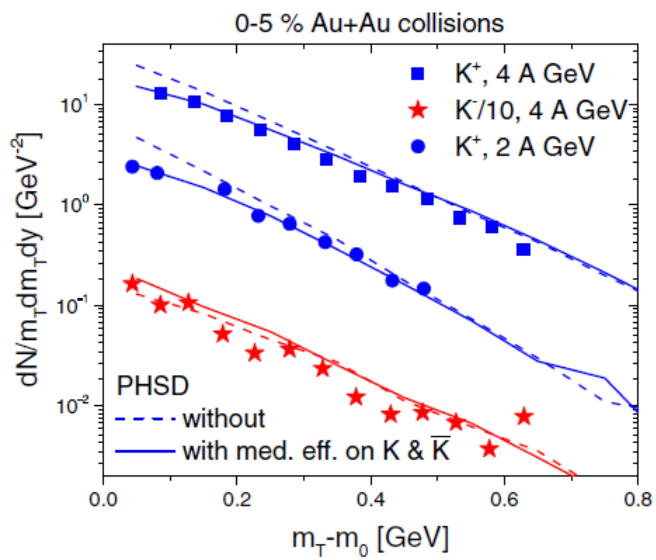
Rapidity and m_T distributions of (anti)kaons at 2-4 AGeV









- **In-medium effects** for K^+ and K^- **improve** agreement with exp. data

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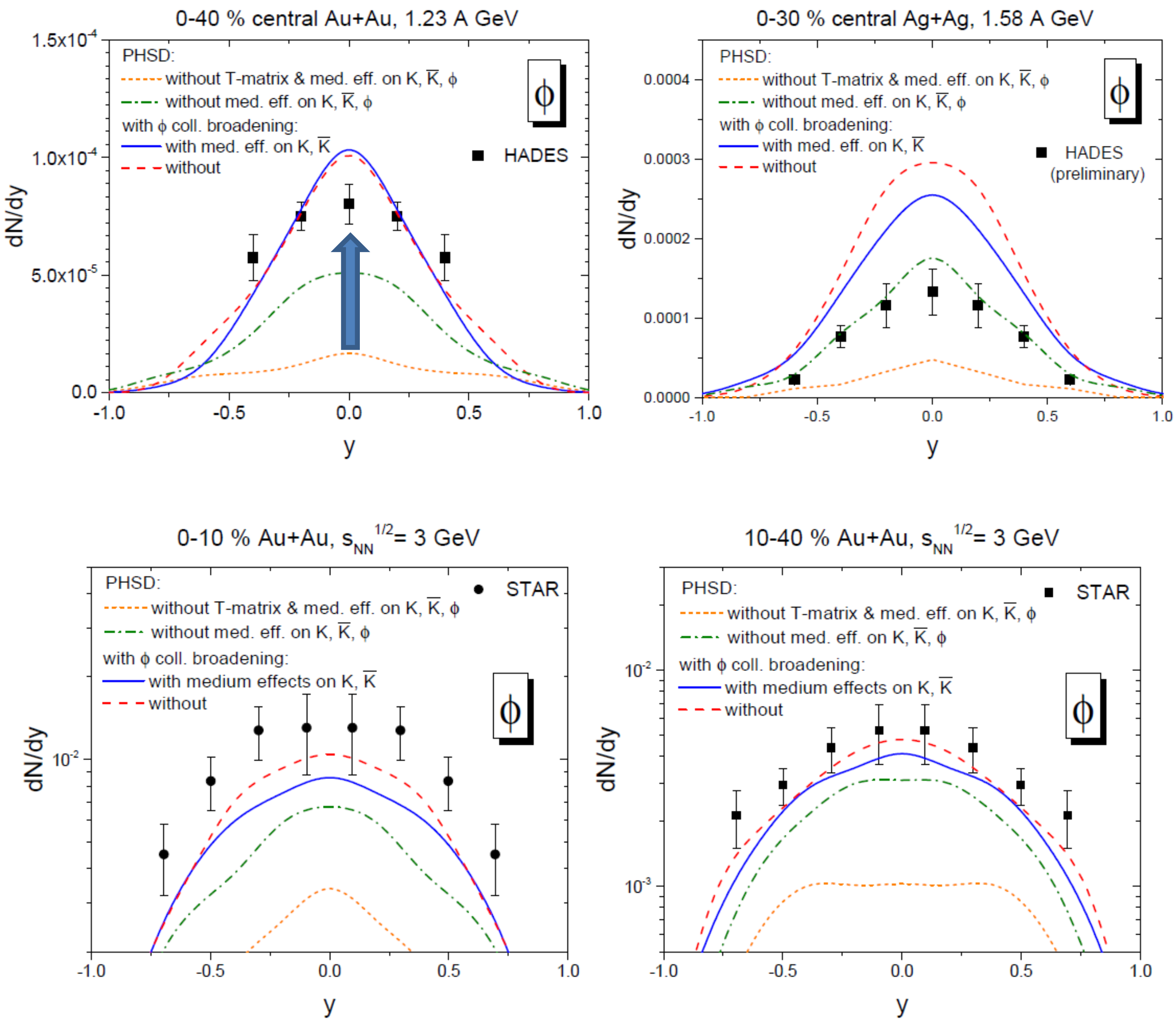
Comparison of ϕ meson dN/dy with HADES & STAR data



Orange: without T-matrix, without coll. broadening – strong underestimation of ϕ production!

Green: with T-matrix, but without coll. broadening

Red: with T-matrix + coll. broadening but without med. eff. on K, Kbar

Blue: all included, i.e. with T-matrix + coll. broadening + med. eff. on K, Kbar

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ϕ/K^- ratio

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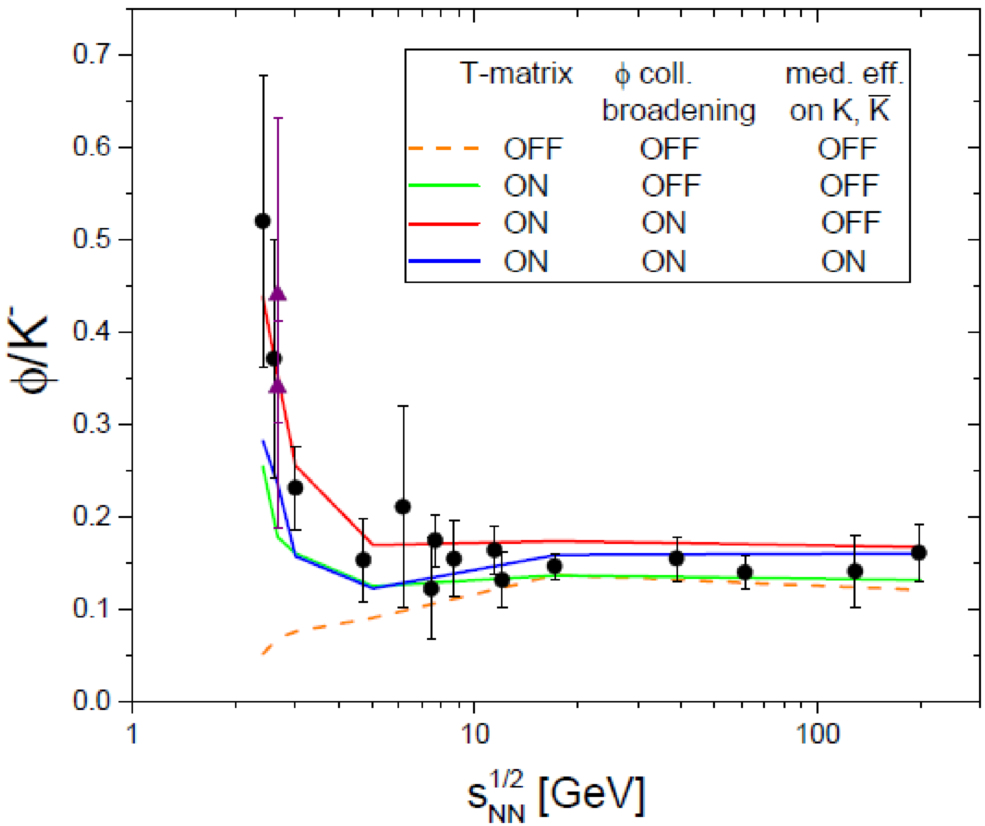

- Orange: without T-matrix & ϕ broadening
  ➔ underestimate the ratio at low energies
- T-matrix (green), T-matrix & ϕ broadening (red) enhance the ratio
- However, medium effects on K, Kbar (blue) suppress it due to the enhanced K^- production at low energy
- At high energies the ratio is less sensitive to the in-medium production by hadronic channels since ϕ's are dominantly produced at QGP hadronization

➔ The "enhanced" ϕ multiplicity and ϕ/K^- ratio close to threshold can be understood without assuming the hypothetic decay N* to ϕ mesons rather by incorporation of in-medium effects + novel mB production channels

Summary

Strangeness production in heavy-ion collisions from (sub-)threshold to high energies is investigated within the PHSD off-shell transport approach.

Novel development:

- **In-medium effects are realized by a G-matrix approach for antikaons, by a linear repulsive nuclear potential for kaons and by collisional broadening of the ϕ meson spectral function**
- **Accounting for additional multistep meson-baryon and meson-hyperon reactions for ϕ meson production as predicted by the SU(6) extension of the meson-baryon chiral Lagrangian within a unitary coupled-channel *T* -matrix approach**

Findings:

- **In-medium collisional broadening enhances ϕ production**
- **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**

➔ The “enhanced” ϕ multiplicity and ϕ/K^- ratio close to threshold can be understood without assuming the hypothetic decay N* to ϕ mesons rather by incorporation of in-medium effects + novel mB and mY production channels

*** Outlook:**

… still tension in the description of HADES data on K^- and ϕ for Au+Au at 1.23 A GeV:
Further robust experimental data are needed (HADES, CBM, BMN,…)!