Properties of K* in a medium

Andrej Ilner

Johann Wolfgang Goethe-Universität Frankfurt am Main
Institut für theoretische Physik
Frankfurt Institute for Advanced Studies

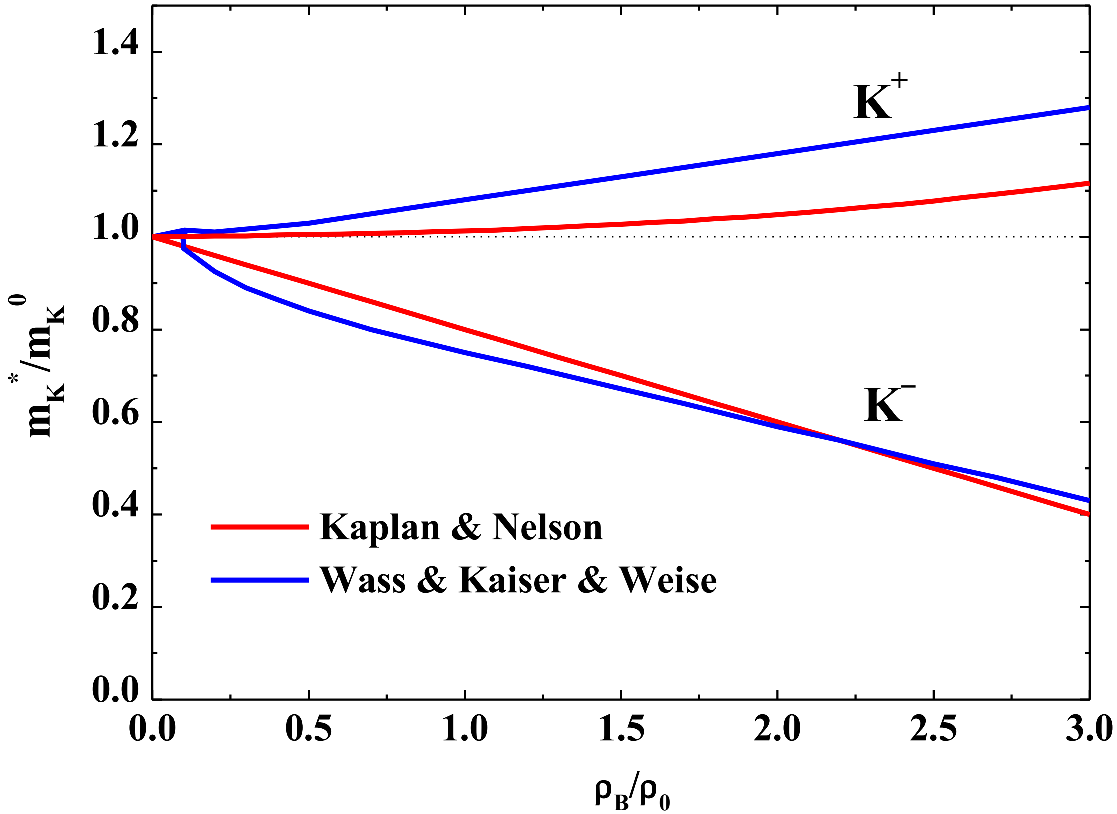
In collaboration with
Daniel Cabrera, Elena Bratkovskaya

2014.06.10
Hersonissos, Crete, Greece

Contents

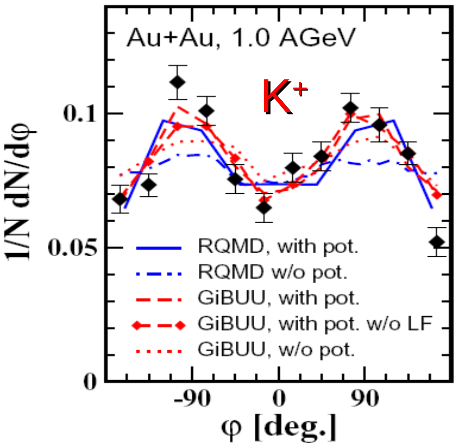
Introduction and motivation

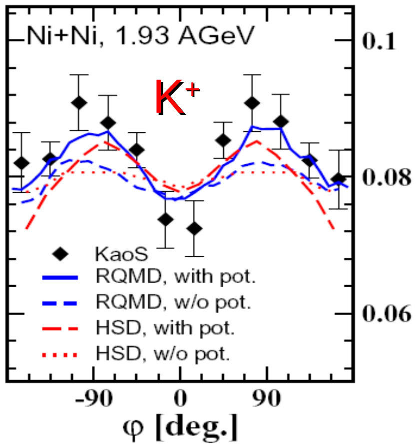
- **In-medium properties of kaons** (K, anti-K, K* and anti-K*)
- First results were obtained using **chiral perturbation theory** (*Kaplan, Nelson, PLB 175 (1986) 57*) and **relativistic mean field models** (*Schaffner, Gal, Mishustin, Stöcker, Greiner, PLB 334 (1994) 268*)
- **Dirac-Brueckner Hartree-Fock** approximation (*Brueckner, PR 97 (1955) 1353; Hjorth-Jensen et al., PR 261 (1995) 125*) applied to **KN system**
- DBHF goes beyond a mean fields and uses realistic KN interactions for the calculations

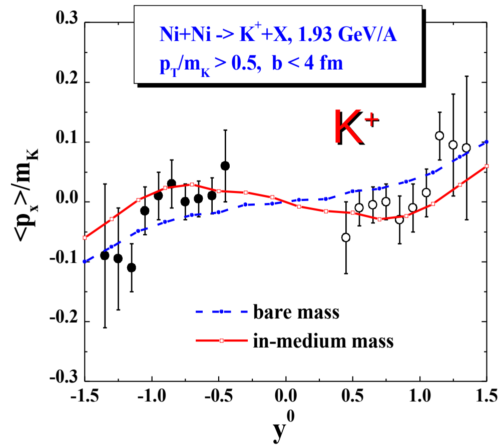


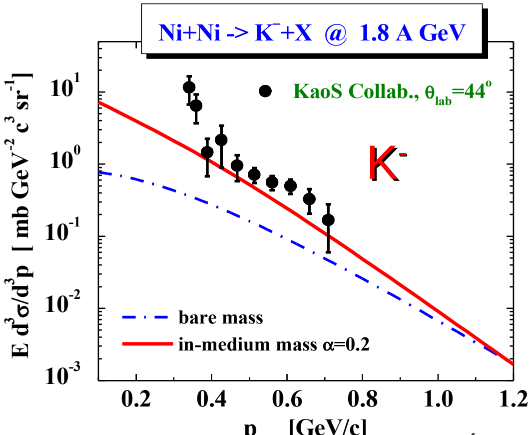
Introduction and motivation

- Experimentally strangeness has been studied since the 1980s
- In-medium properties are studied e.g. in heavy-ion collisions
- For baryonic matter at SIS (and in the future at FAIR) etc. energies
- For hot nuclear matter at RHIC, LHC etc. energies
- Later KaoS collaboration published results which agreed with theoretical predictions **when including K / anti-K in-medium effects**









Figs. by E. Bratkovskaya et al.

Introduction and motivation

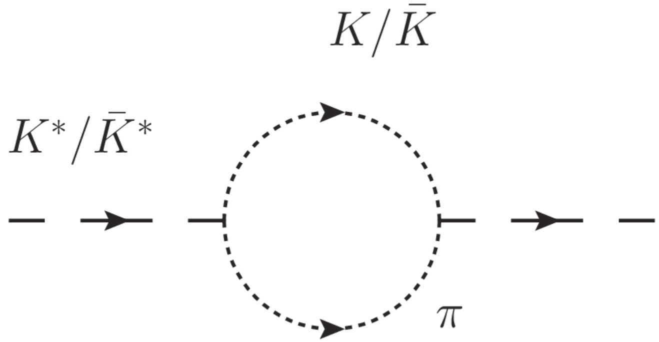
- **Goal: study in-medium <u>strange pseudoscalar</u> and <u>vector mesons</u> within Breit-Wigner approach in a consistent way, for a convenient implementation in transport models of strangeness production in HICs**

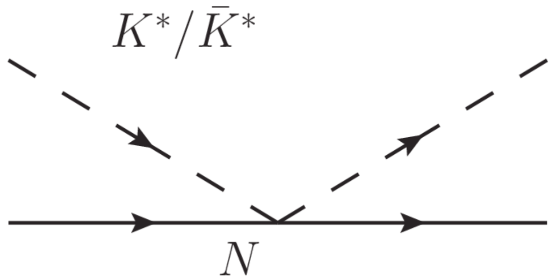
***1. <u>Dense nuclear matter (FAIR)</u>*:** self-consistent coupled-channel approach ("G-matrix")

- K* and anti-K* modified from **K*N** and **K*** → **K π** [***different behaviour!***]
- K* self-energy within the unitarised chiral perturbation theory [***NEW!***]

2. <u>Hot nuclear matter (RHIC/LHC)</u>: results from Chiral Perturbation Theory in hot meson gas

- K* and anti-K* in-medium effects from **K*** → **K π** coupling [behave similarly]
- Estimation of the real part of the K* self-energy [***mass shift!***]





Framework

- **G-matrix** results are approximated by the **Breit-Wigner** spectral function
- Evaluation of in-medium **widths** and **masses**, which are connected to **imaginary** and **real** part of the **self-energy** of strange mesons
- Approximation implicitly neglects momentum dependence of self-energy

Framework

The meson propagator (*i = K, anti-K; K*, anti-K**)

$$D_i(\omega,\vec{q},\rho)=\frac{1}{\omega^2-\vec{q}^2-m_i^2-\Pi_i(\omega,\vec{q},\rho)}$$

$\omega: energy$

$\vec{q}: momentum$

$m_i: pole\ mass$

$\Pi_i: Self-energy$

$\rho: baryon\ density$

Spectral function

$$S_i(\omega,\vec{q},\rho)=-\frac{1}{\pi}\Im(D_i(\omega,\vec{q},\rho))=-\frac{1}{\pi}\frac{\Im(\Pi_i(\omega,\vec{q},\rho))}{\left|\omega^2-\vec{q}^2-m_i^2-\Pi_i(\omega,\vec{q},\rho)\right|^2}$$

Spectral function rewritten in a way more similar to the Cauchy-Lorentz distribution

$$S_i(\omega,\vec{q},\rho)=-\frac{1}{\pi}\frac{\Im(\Pi_i(\omega,\vec{q},\rho))}{[\omega^2-\vec{q}^2-(m_i^2+\Re(\Pi_i(\omega,\vec{q},\rho)))]^2+[\Im(\Pi_i(\omega,\vec{q},\rho))]^2}$$

Framework

Spectral function in the Breit-Wigner approach

$$A_i(M,\rho)=C_1\frac{2}{\pi}\frac{M^2\Gamma_i(M,\rho)}{(M^2-M_0^*(\rho)^2)^2+(M\,\Gamma_i(M,\rho))^2}$$

$\Gamma_i : width$

$M : (off-shell)\, mass$ or $energy$

$M_0 :$ in$-medium\, mass$

$C_1 : normalisation\, constant$

For q=0 a connection between the imaginary part of the meson propagator and the Breit-Wigner spectral can be established.

$$A_i(M,\rho)=2\cdot C_1\cdot M\, S_i(M,\rho)$$

The following relations follow from that connection.

$$M_0^{2*}=m_i^2+\Re(\Pi_i(M,\rho))$$

$$\Gamma_i(M,\rho)=-\frac{\Im(\Pi_i(M,\rho))}{M}$$

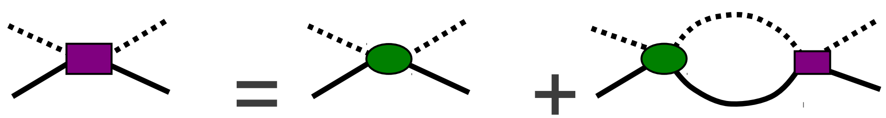
Spectral function is normalised

$$\int_0^\infty A_i(M,\rho)\,dM=1$$

Energy dependence is omitted

Dense matter

- Dense matter scenario: results from meson-baryon T (or G)-matrix in Dirac-Brueckner Hartree-Fock.
- Self-consistency, coupled-channels and unitarity.
- The Bethe-Salpeter equation in coupled channels is solved for the in-medium scattering amplitude.



Medium: $T_{ij}(\rho) = V_{ij} + V_{il}\, G_l(\rho)\, T_{lj}(\rho)$

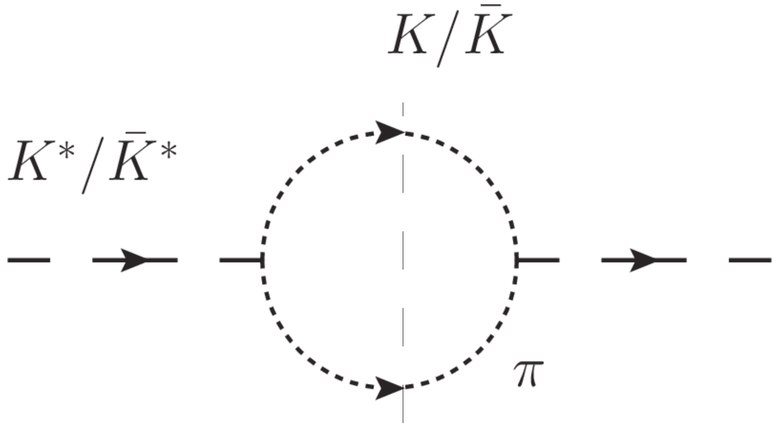
Koch
Kaiser, Waas , Weise
Lutz, Kolomeitsev;
Schaffner-Bielich
Ramos, Oset, Tolos

Oller, Meissner
Hosaka, Jido
Nieves, Ruiz-Arriola
Cassing, Bratkovskaya, Tolos, Ramos

- V : LO interaction from chiral Lagrangian
  - KN: meson baryon ChPT (coupling of octet of pseudoscalar mesons to the octet of $J^P=1/2^+$ baryons)
  - K*N: Hidden Local Gauge Symmetry Lagrangian (vector-meson octet)
- G : dressed in-medium meson-baryon propagator, including Pauli blocking on nucleon states, baryon potentials and meson self-energies.

Dense matter

- **Additional contribution for strange vector mesons:** K* decays into Kπ (two-meson cloud effects)



- It is possible to account for the in-medium width of the K*→Kπ mode by incorporating the K spectral function
- *Pions* are also expected to experience in-medium modifications. Neglect this effect for simplicity (future work).

Dense matter

The (p-wave) decay width of the K*

$$\Gamma_{Kstar}(\mu,\rho)=\Gamma_0\left(\frac{\mu_0}{\mu}\right)^2\cdot\frac{\int_{M_{min}}^{\mu-m_\pi}A_K(M,\rho)\cdot q(\mu,M)^3\,dM}{\int_{M_{min}}^{\mu_0-m_\pi}A_K(M,0)\cdot q(\mu_0,M)^3\,dM}$$

M : *off - shell mass of the K*

μ : *off - shell mass of the K**

with

$$q(\mu,M)=\frac{\sqrt{\lambda(\mu,M,m_\pi)}}{2\mu} \qquad q(\mu_0,M)=\frac{\sqrt{\lambda(\mu_{0,}M,m_\pi)}}{2\mu_0}$$

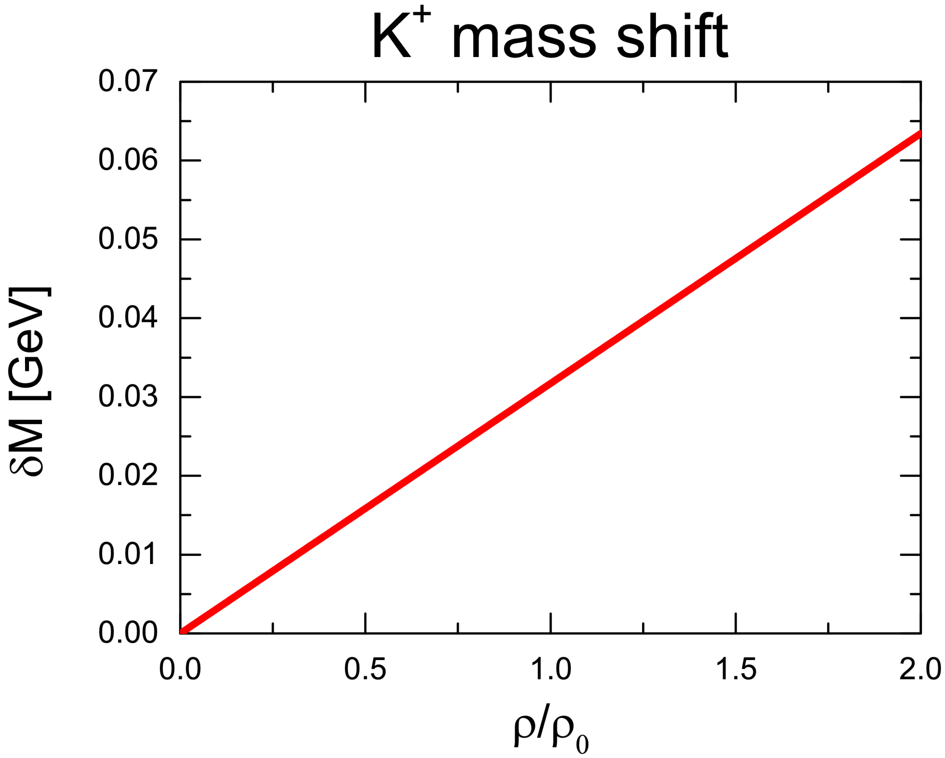
This is a similar approach that was also used for the $\mathbf{a_1}$ decaying into **π ρ**.

Dense matter: Kaons

- In a dense nuclear medium K behaves like a narrow quasi-particle (KN interaction smooth;

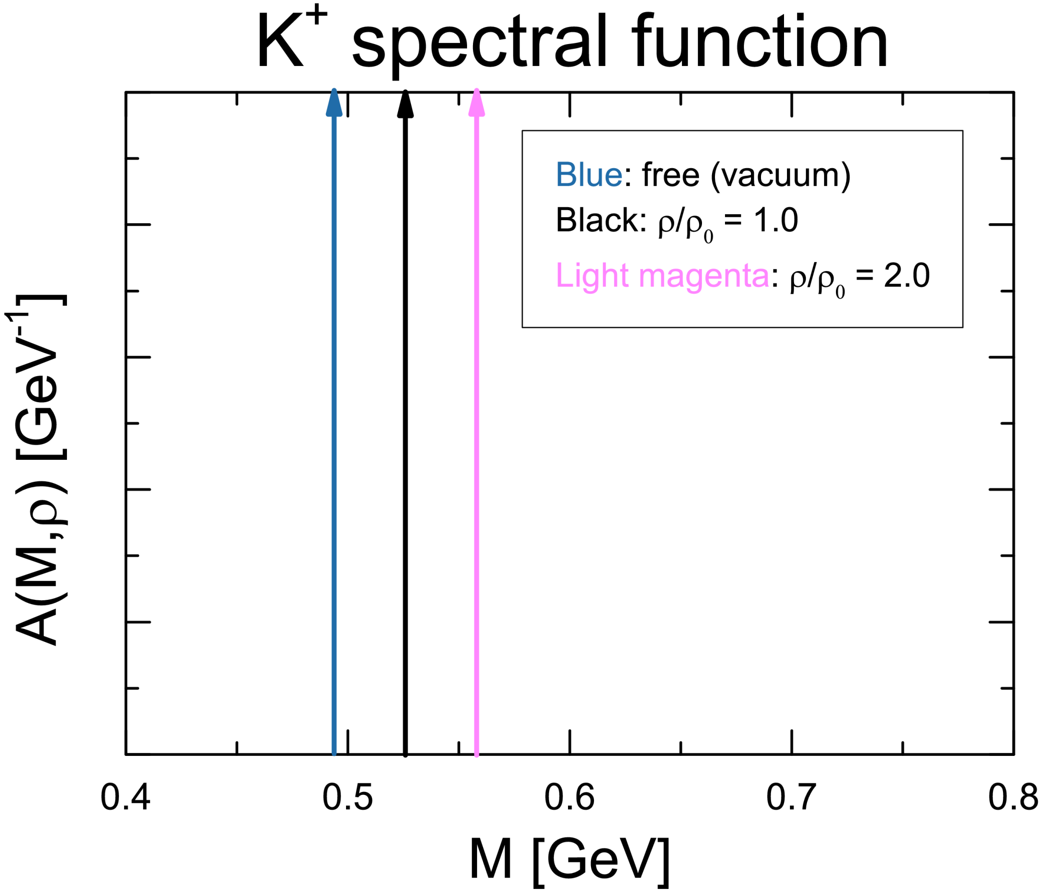
  Kaiser, Siegel, Weise NPA594 (1995) 325; Oset, Ramos, NPA635 (1998) 99

- Neglect imaginary part of self-energy
- Re Π ↔ mass shift from chiral Lagrangian dynamics in a ***t-ρ*** approximation



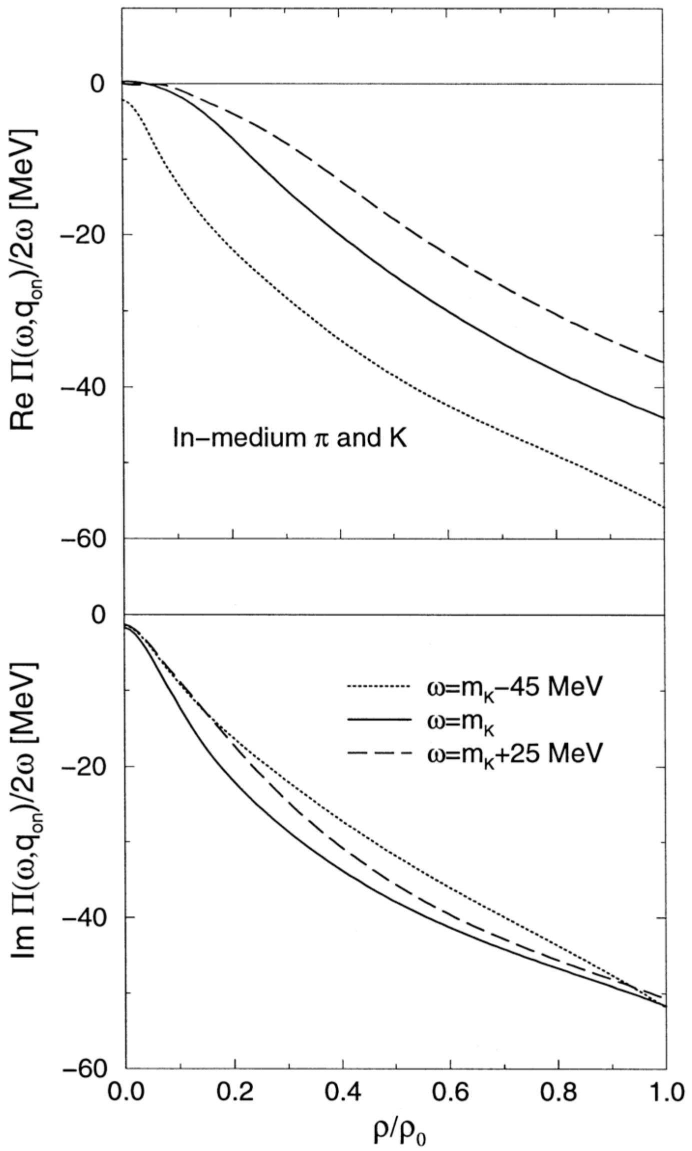
Dense matter: Kaons

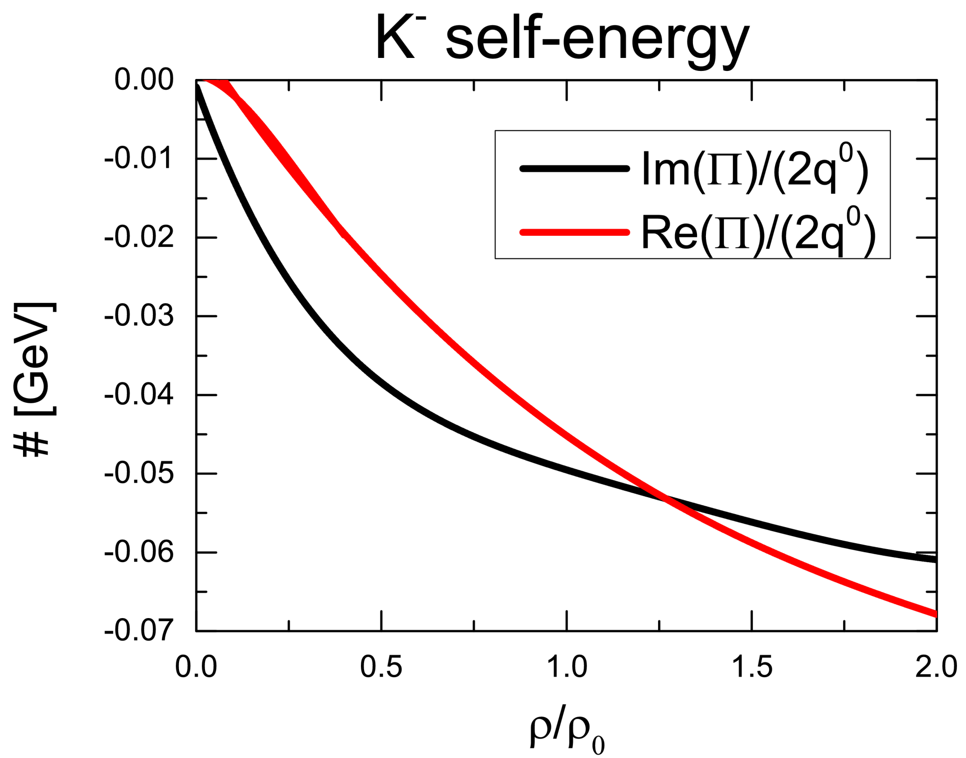
- The K has almost no broadening and behaves like a stable particle when increasing nuclear density (the "full" calculation leads to a very small width)
- K experiences a repulsive potential → spectral function gains a positive mass shift



Dense matter: anti-Kaons

- Self-energy by Ramos et al. from G-matrix approach with ChPT, **anti-K N → Λ(1405)**!
- Results were extrapolated to higher densities (i.e. beyond normal density), assuming some saturation

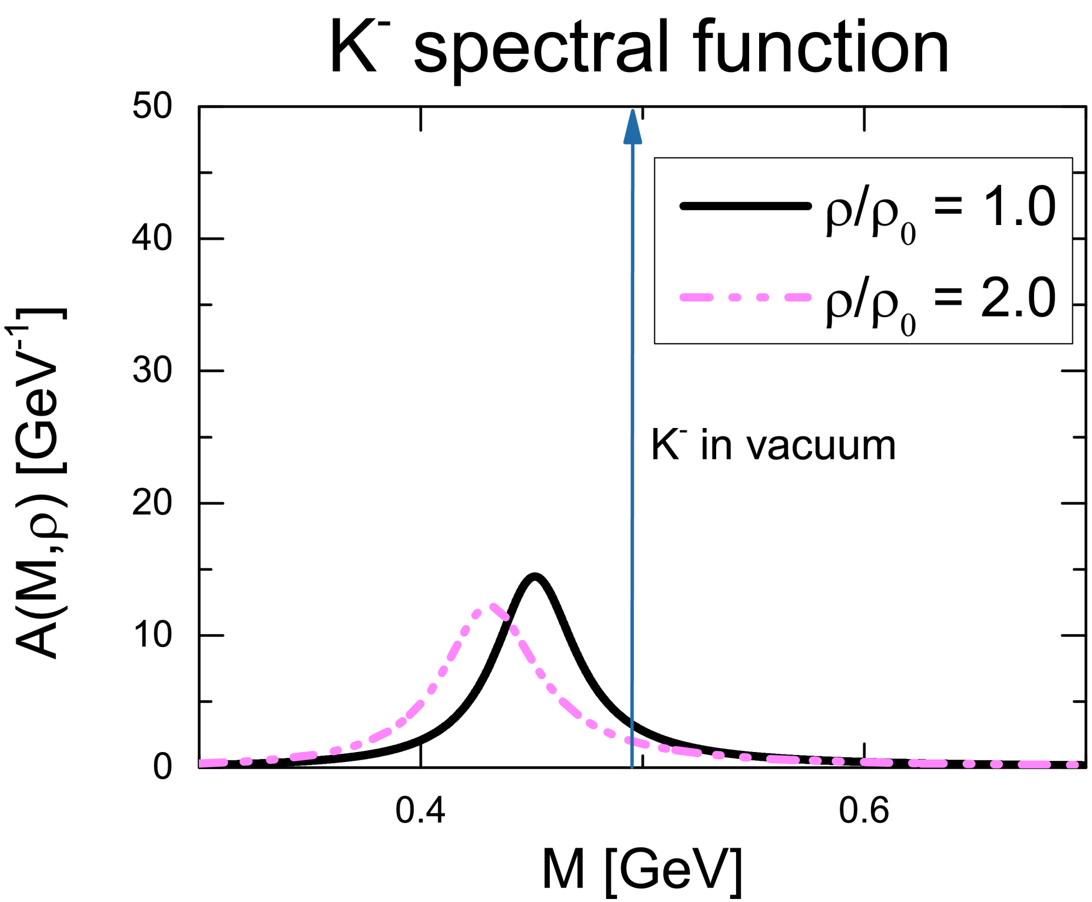




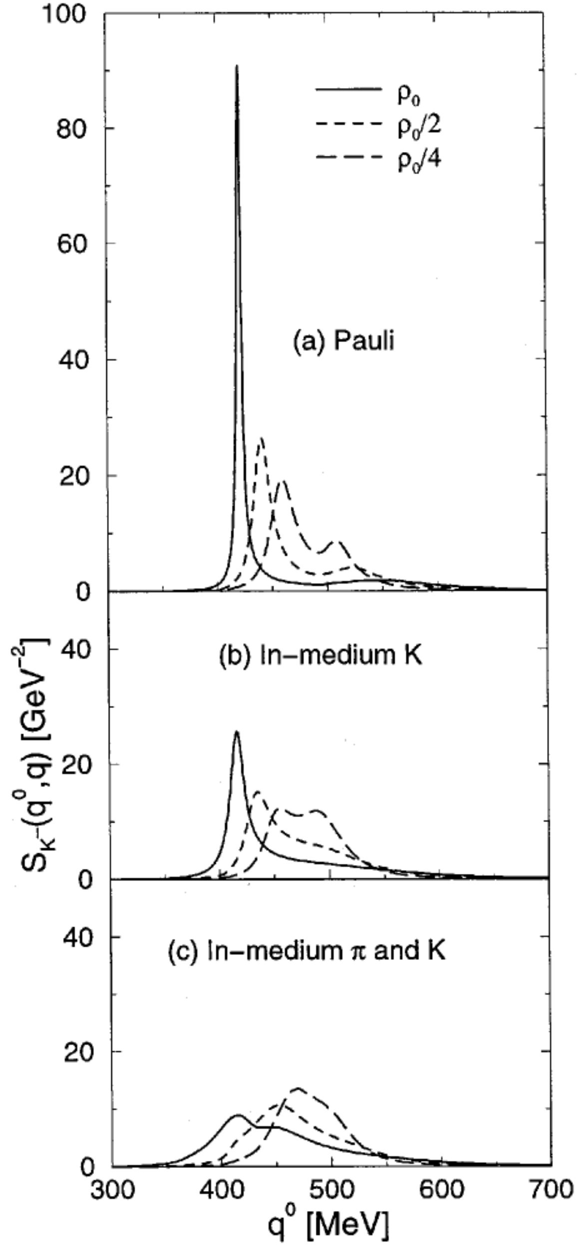
Ramos, Oset, NPA 671 (2000) 481

Dense matter: anti-Kaons

- Spectral function for the anti-K
- In vacuum the particles are stable (Dirac delta)
- The anti-K experiences an **attractive potential** → negative mass shift
- And **considerable broadening**!
- (detailed structure of excitations not retained)



Ramos, Oset, NPA 671 (2000) 481



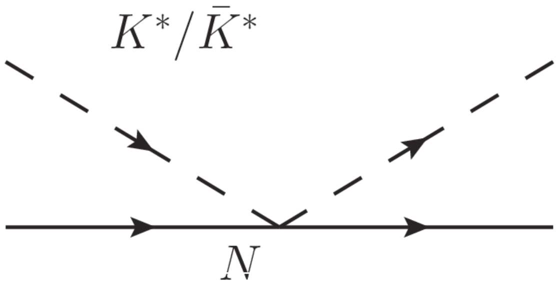
Dense matter: K*

- **New contribution: K* self-energy from K*N interaction**
- The K* in a dense nuclear medium can be treated just like the K with respect to the self-consistent chiral coupled-channel calculations based on chiral dynamics (*Tolos et al PRC87 (2010) 045210; Oset et al EPJA44 (2010) 445*)
- Same expression for the transition potential for K*N as for the KN, also for the self-energy

$$\Pi(q^0,\vec{q},\rho)=2\int \frac{n(\vec{p})}{(2\pi)^3}\left[T_{K*p}(p^0,\vec{p},\rho)+T_{K*n}(p^0,\vec{p},\rho)\right]d^3p\approx\frac{1}{2}\left(T_{K*p}(\rho)+T_{K*n}(\rho)\right)\rho$$

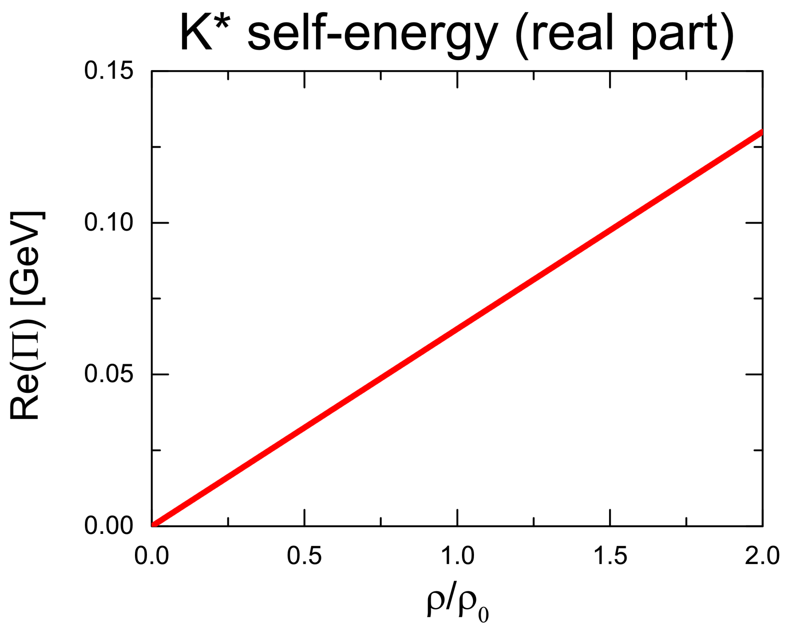
- ***t-ρ*** approximation (no resonances in K*N), Π accounts for K* mass shift
- We have unitarised the interaction matrix using the Bethe-Salpeter equation

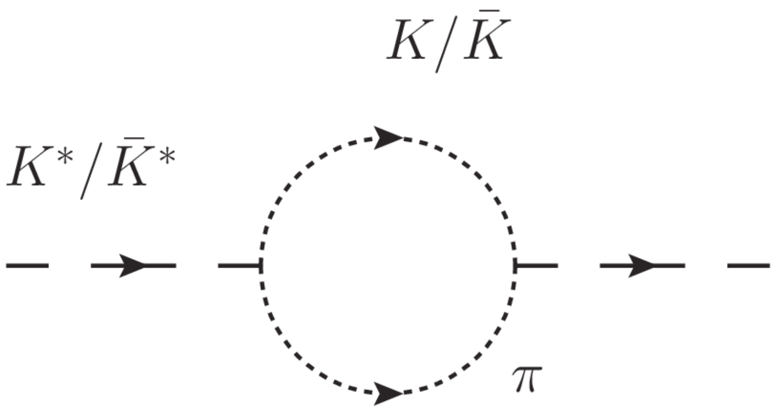
T = V/(1 – VG)

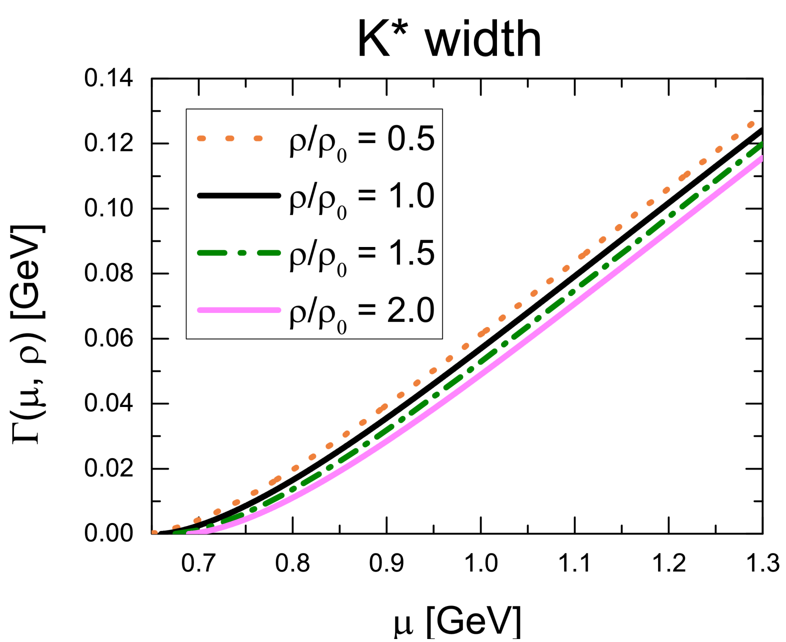


Dense matter: K*s

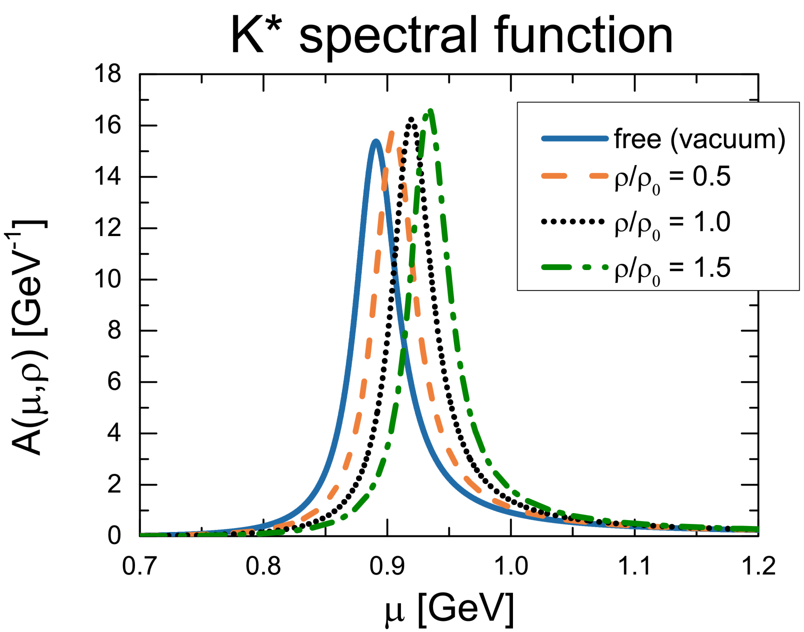
- Real part obtained from self-energy expression (previous slide)
- Width of K* self-energy calculated through in-medium modification via K* → K π
- Width changes moderately (decreases)

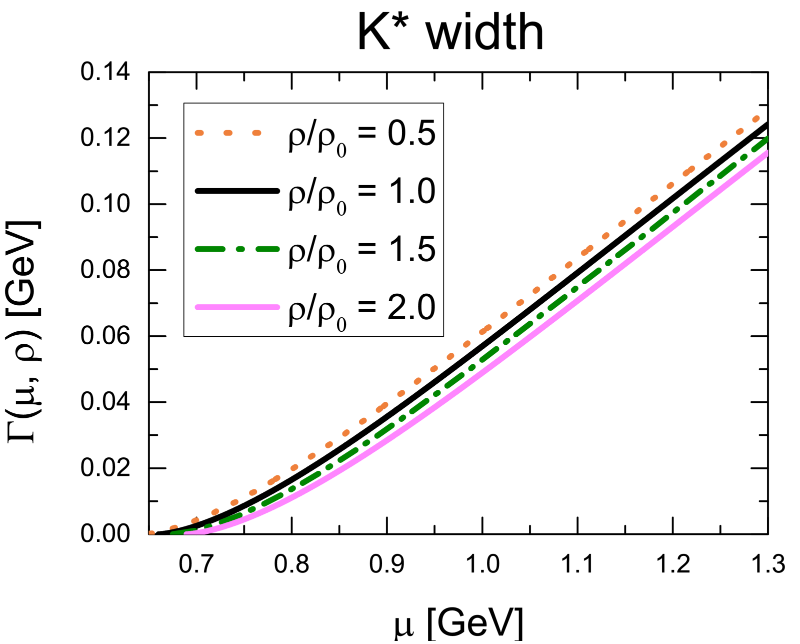






Dense matter: K*s

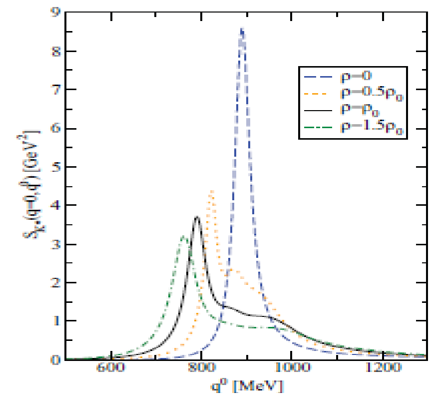




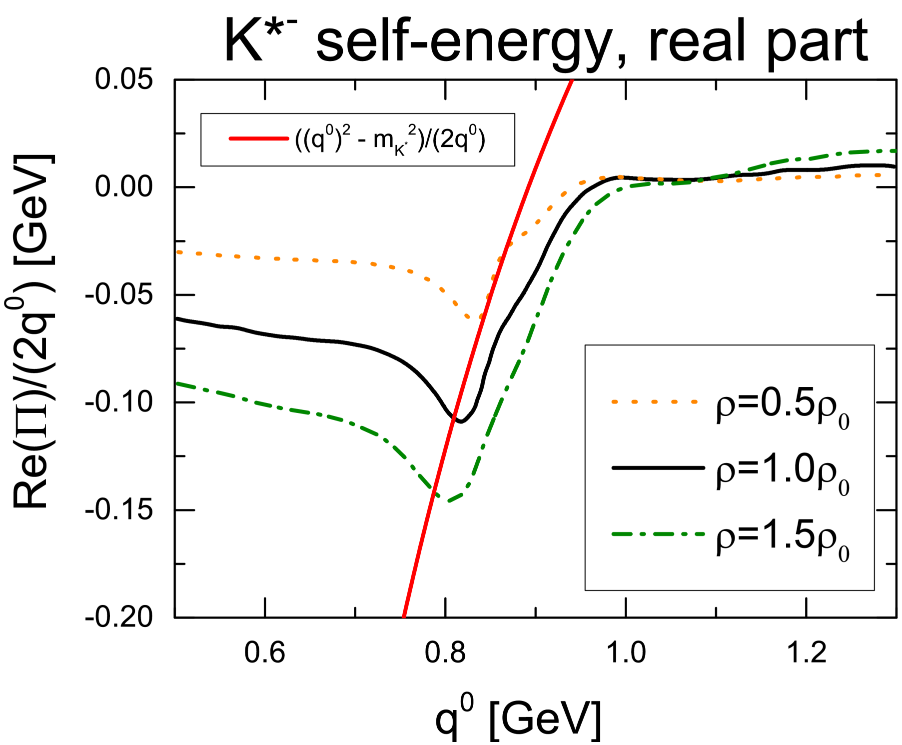
- K* experiences repulsive medium, spectral function shifted to higher masses
- As density increases → K* width is actually lower due to the heavier Kaon in K* → Kπ
- The two effects compensate: shape of K* spectral function practically unchanged

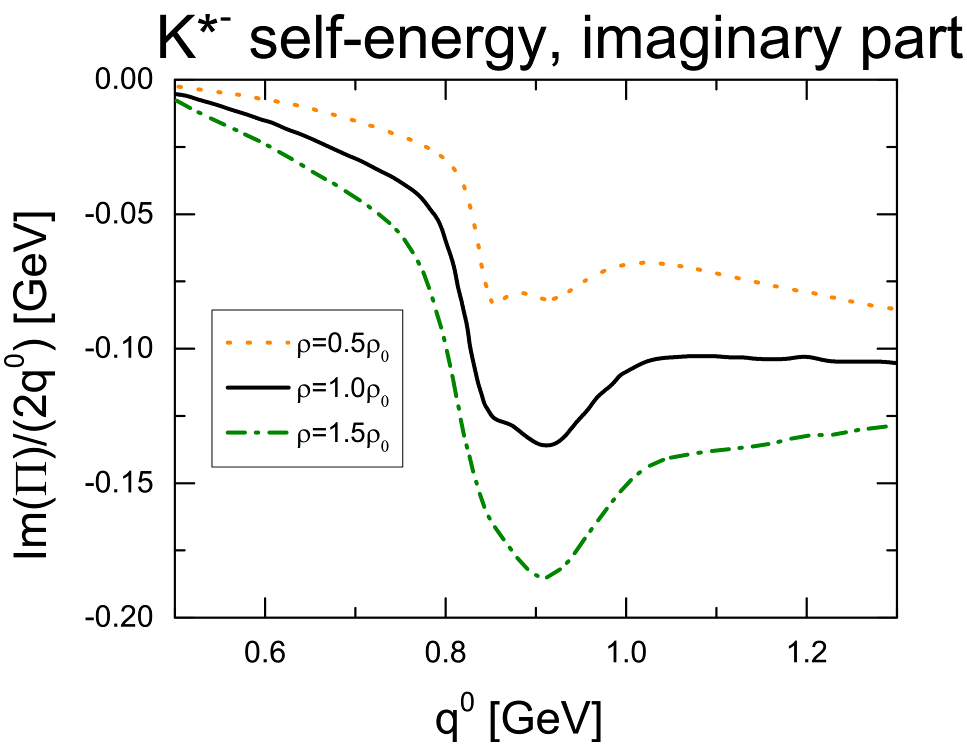
Dense matter: anti-K*s

- **anti-K* N**: dynamics ruled by S=-1 resonances (as for anti-K) → complicated ***many-body structure*** and ***E-dependence*** of self-energy
- Parametrise full G-matrix calculation [*Tolos et al PRC87 (2010)*]
  - 1. Solve dispersion relation: quasi-particle energy ω_{K^*}
  - 2. Use ω_{K^*} to find width: $\Gamma_{K^*} = \mathrm{Im}\,\Pi_{K^*} / \omega_{*}$



Tolos et al., PRC 82 (2010) 045210

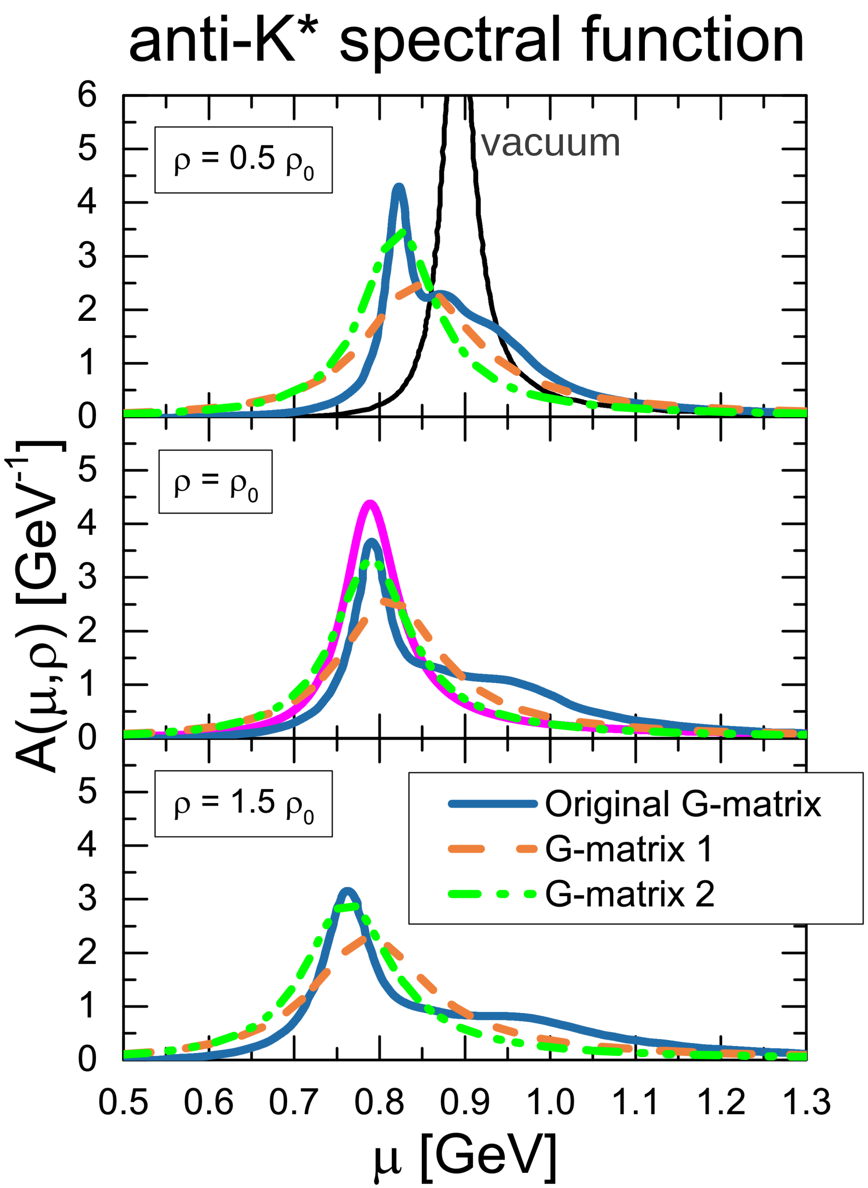




Dense matter: anti-K*s

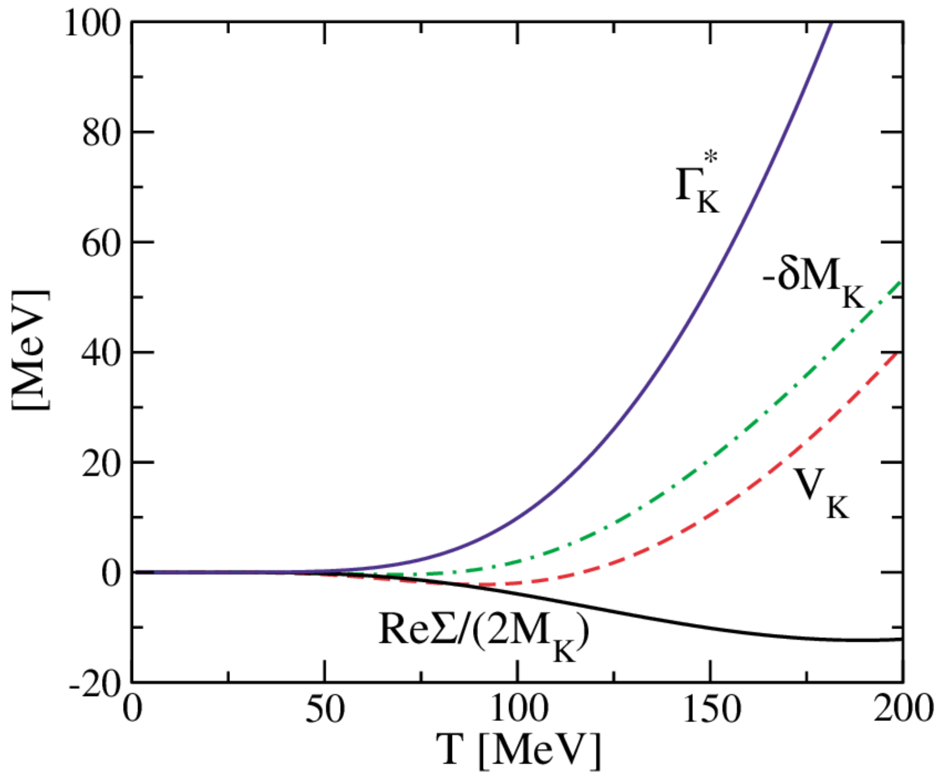
- Blue: Original G-matrix calculation
- Orange: Breit-Wigner spectral function
- Green: Breit-Wigner spectral function with corrected mass shift
- Middle plot: Magenta line denotes evaluation of Kπ width with in-medium kaons

- Breit-Wigner does not retain multi-pole structure and overestimates the strength at low energies, but ***keeps essential features***



Hot matter: kaons

- Consider hot, isotopically symmetric gas of pions: K* and anti-K* identical
- Medium effects tied to **K*→K π decay mode**
- **K in hot pion gas**: evaluated by Martemyanov *et al.* in meson-meson ChPT + phenomenological extension for higher energies
- (pions considered stable)

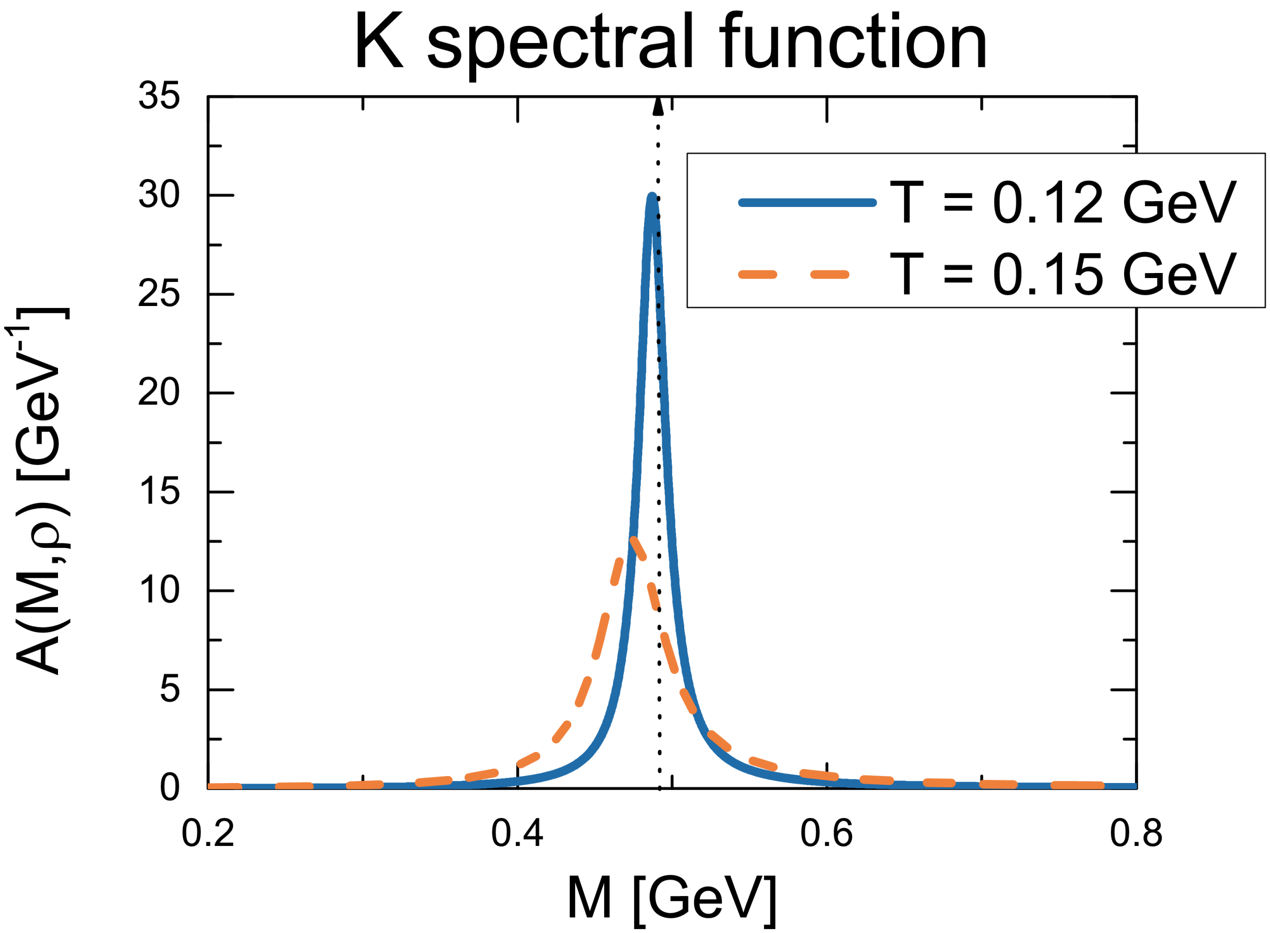


The quantities of interest in this case are the width Γ_K and the mass shift δM_K to build the **K* selfenergy**

Martemyanov et al., PRL 93 (2004) 052301

Hot matter: kaons

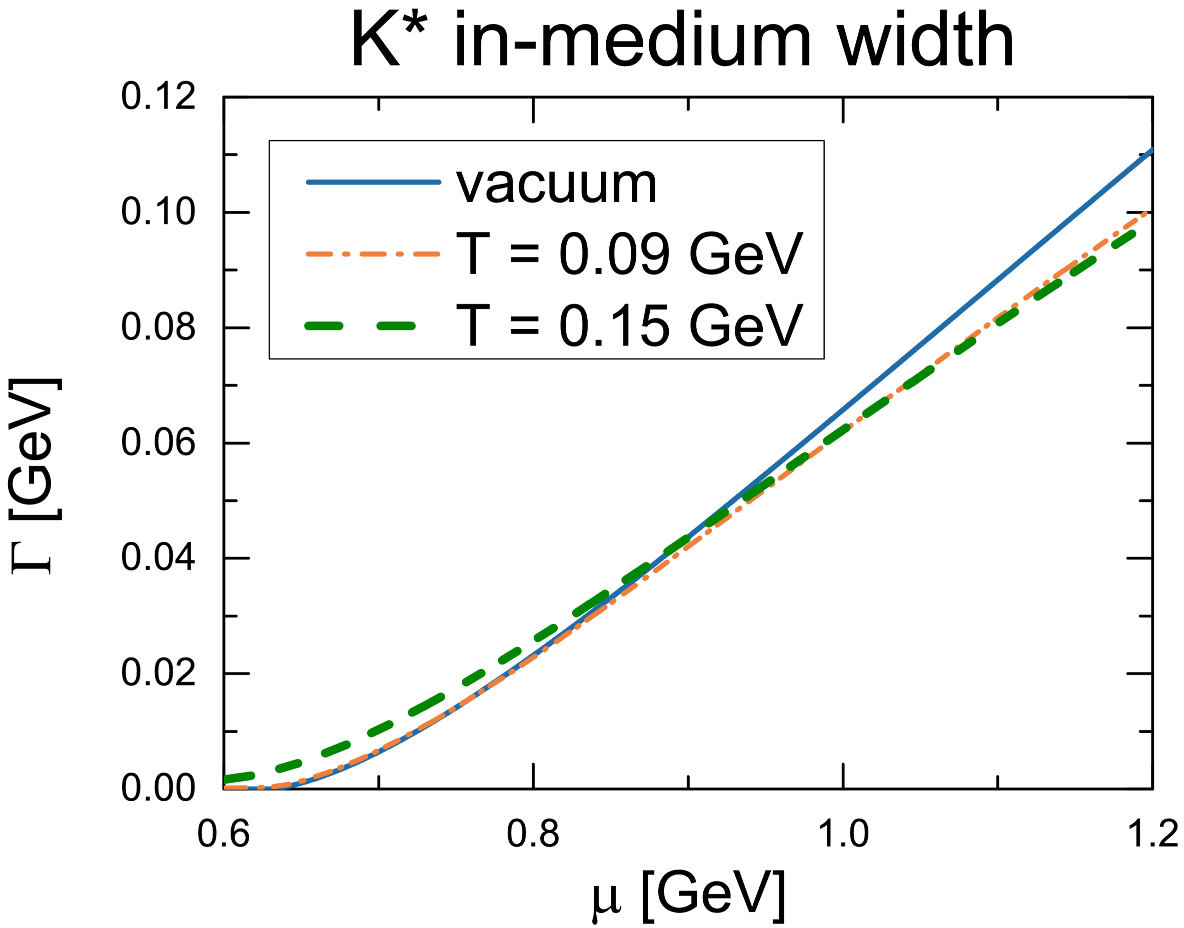
- Use Breit-Wigner to construct K spectral function at different temperatures



Hot matter: K*s

- Use K spectral function to obtain K* width

$$\Gamma_{K^*}(\mu,\rho)=\Gamma_0\left(\frac{\mu_0}{\mu}\right)^2\cdot\frac{\int_{M_{min}}^{\mu-m_\pi} A_K(M,\rho)\cdot q(\mu,M)^3\,dM}{\int_{M_{min}}^{\mu_0-m_\pi} A_K(M,0)\cdot q(\mu_0,M)^3\,dM}$$



Hot matter: K*s

- Use dispersion relation to calculate the real part using the imaginary part of the self-energy!

$$\Re\left(\Pi(\mu)\right)-\Re\left(\Pi_{vac}(\mu)\right)=-\frac{2}{\pi}\int_{m_\pi}^{\infty}\frac{\mu'}{\mu'^2-\mu^2}\left[\Gamma^{dec}(\mu',T)-\Gamma^{vac}(\mu')\right]d\mu'$$

- Unfortunately the emerging integral is divergent
- Use phenomenological form factor in K* -> K π vertex to regularise integral

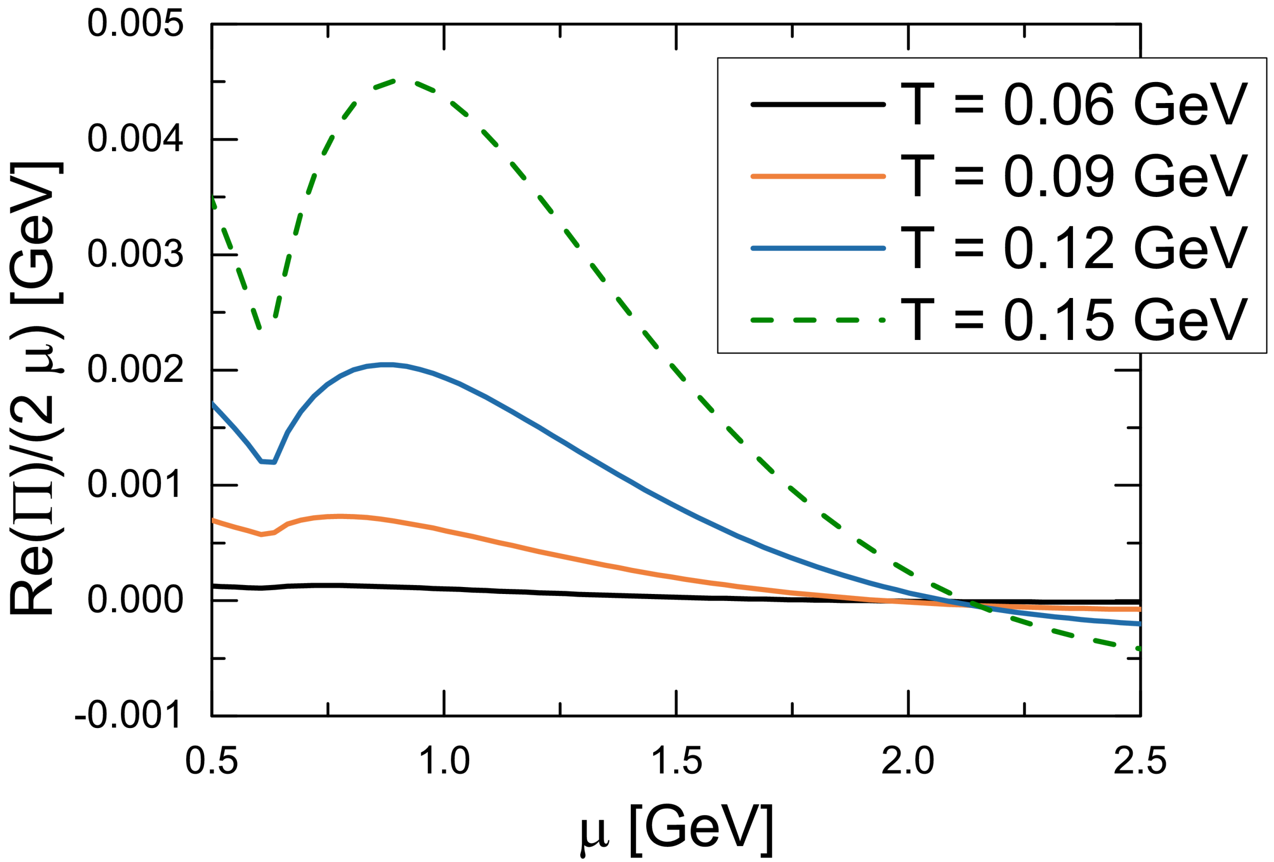
$$F(\Lambda,\mu)=\left(\frac{\Lambda^2+q(\mu_{0,}M_0)^2}{\Lambda^2+q(\mu,M)^2}\right)^2$$

M : *off - shell mass of the K*
μ : *off - shell mass of the K* *
μ_0 : *pole mass of the K*
M_0 : *pole mass of the K* *

$$q(\mu,M)=\frac{\sqrt{\lambda(\mu,M,m_\pi)}}{2\mu}\qquad q(\mu_0,M)=\frac{\sqrt{\lambda(\mu_0,M_{0,}m_\pi)}}{2\mu_0}$$

Hot matter: K*s

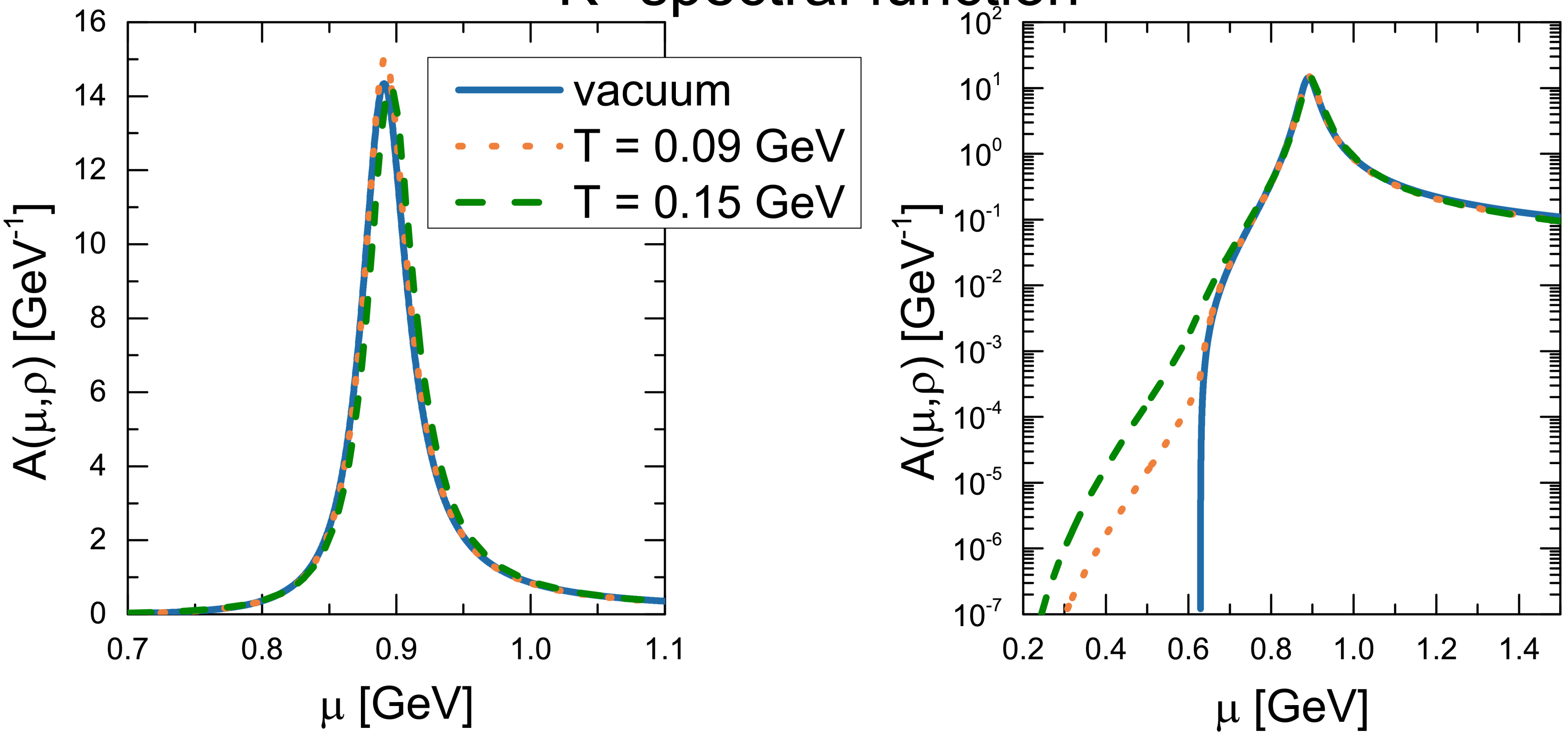
- This results in the following real part of the self-energy (↔ mass shift) (***repulsive and VERY small***)



Hot matter: K*s

- We obtain the following spectral function (for different temperatures)
- Spectral function is fairly stationary with respect to temperature
- Barely any broadening at the qp peak (some strength below threshold)

K* spectral function



Summary and outlook

- The in-medium properties and the behaviour of the strange mesons K, anti-K, K* and anti-K* bar in a hot, pionic and dense, baryonic nuclear medium have been studied within a Breit-Wigner parametrisation of the spectral function.
- In dense nuclear matter, the S=+1 mesons keep their vacuum structure, and can be easily cast in BW form with mild changes in their masses and widths.
- In the S=-1 sector, only an approximate (“average”) description of the spectral function is achieved, retaining essential features as attractive potential and broadening.
- A new contribution for the K* self-energy in dense matter was calculated in ChPT, leading to a positive mass shift 40 MeV at normal matter density.
- In hot hadronic matter, the K* experiences a mild broadening and negligible mass shift only at very high temperatures, from changes in the kaon spectral function.
- These results can now be implemented into transport models and used in simulations to get more realistic behaviour for strange particles in HICs.

The end.

Thank you for your attention.