Constraints of the EoS of strongly interacting matter and on particle properties from relativistic heavy ion collisions

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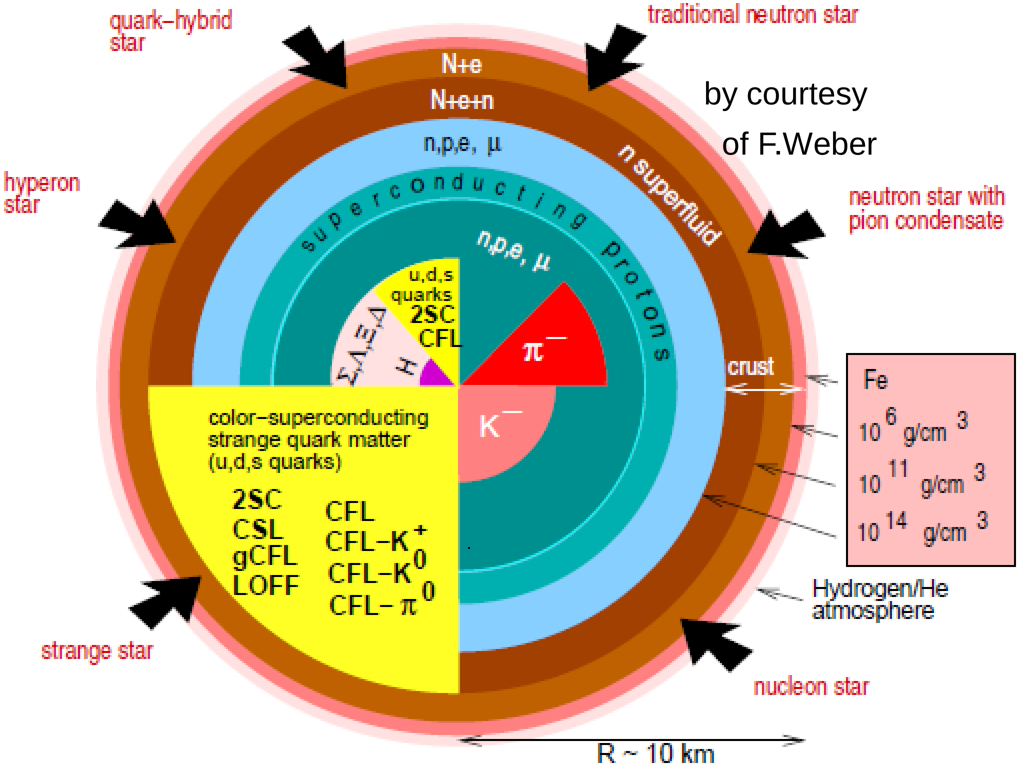
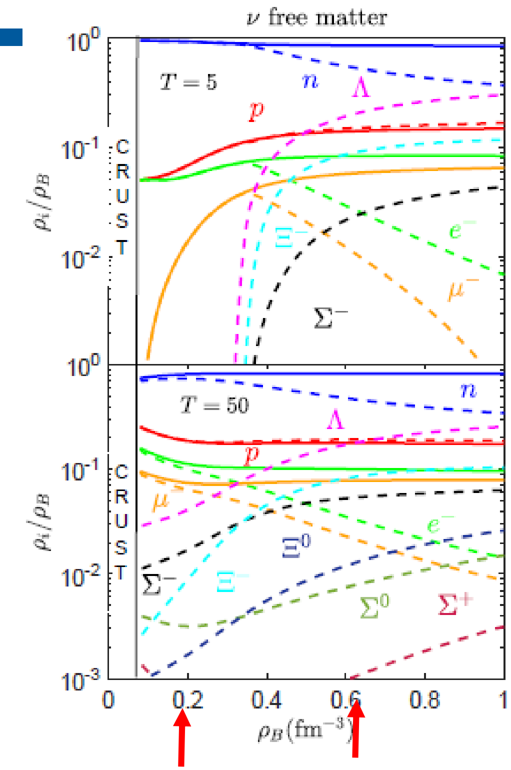
What we want to understand: neutron stars



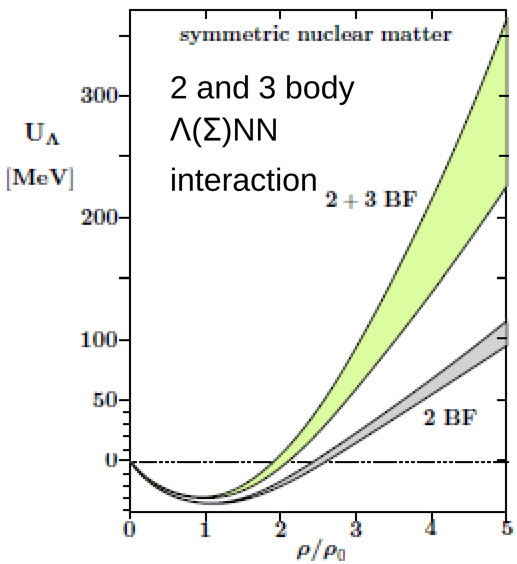
by courtesy of F.Weber

Kochankovski et al. (Barcelona) 2206.11266 (SU(3) CPT)

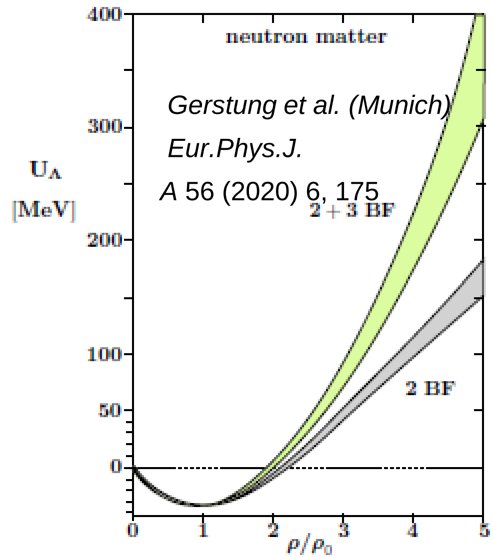
full:no hyperons, dashed:hyperons



ρ_0 $3\rho_0$



2 and 3 body Λ(Σ)NN interaction



Gerstung et al. (Munich)
Eur.Phys.J. A 56 (2020) 6, 175

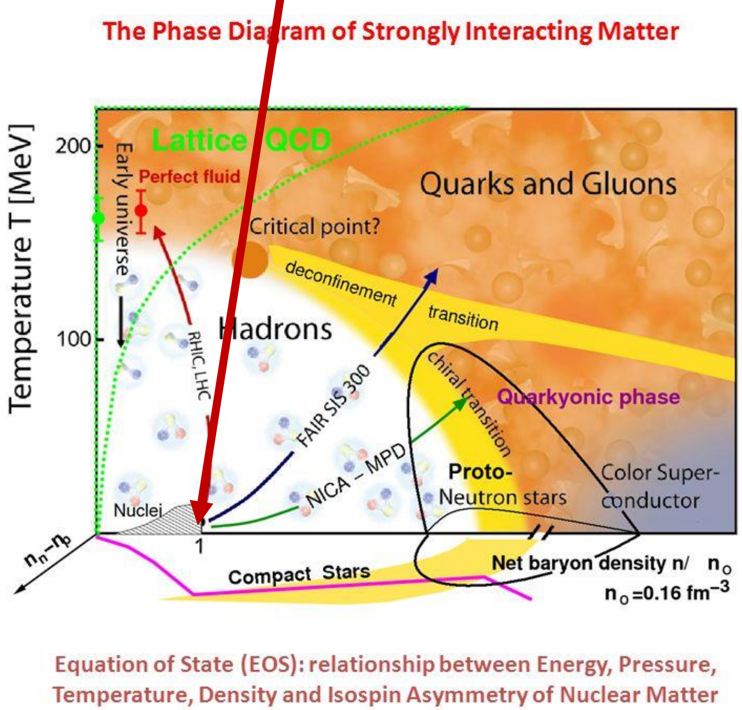
Multiplicity depends strongly on the model (parameters)

… and on the order of the interaction

Study of neutron stars ↔ search for nucl. equation of state (EoS)

How much energy does it cost to heat or to compress matter ?

Only point known
(extrapol. from cold nuclei)



besides NS only heavy ion experiments explore part of (T,μ(ρ)) region

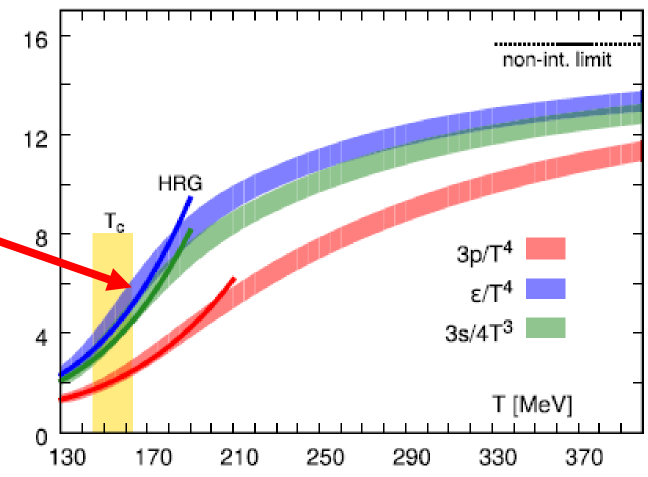
but the EoS is not an observable

several strategies possible

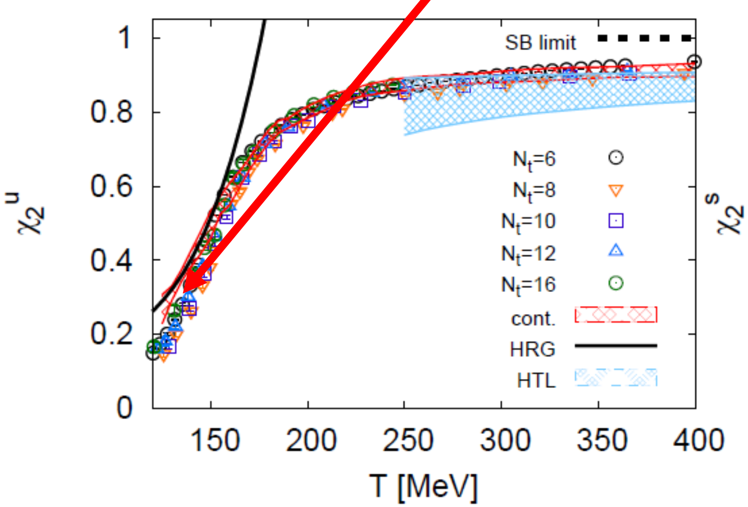
- Lattice QCD (but only at small μ)
- effective theories (NS and HI)
  Nambu Jona-Lasinio
  dynamical quasi particle model
  chiral perturbation theory
- Collecting knowledge from experiment

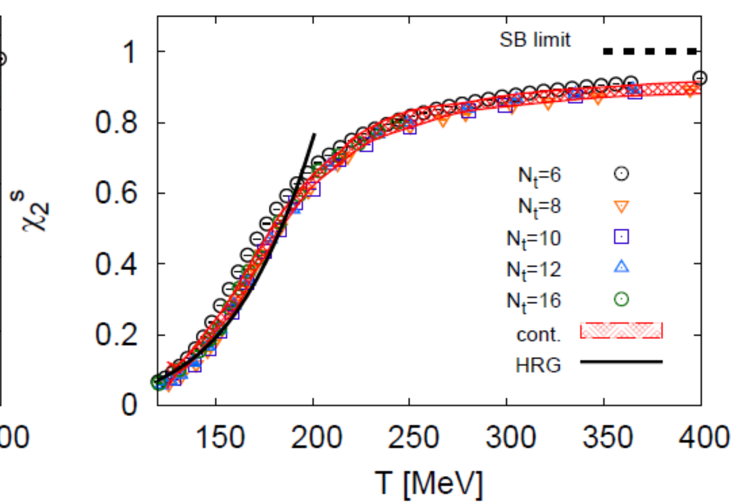
QCD Lattice calculation (limited to μ=0) and the hadrons resonance gas

Lattice calculations and hadron gas seem to have a smooth transition

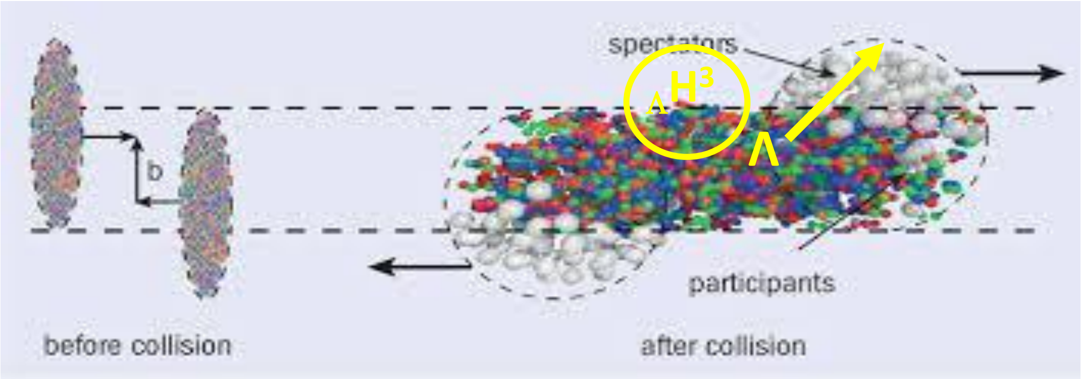


$$\chi_2^u = \frac{T}{V}\frac{\partial^2 \ln Z}{\partial\mu_u\partial\mu_u}\bigg|_{\mu_i=0} \qquad \chi_2^s = \frac{T}{V}\frac{\partial^2 \ln Z}{\partial\mu_s^2}\bigg|_{\mu_i=0}$$





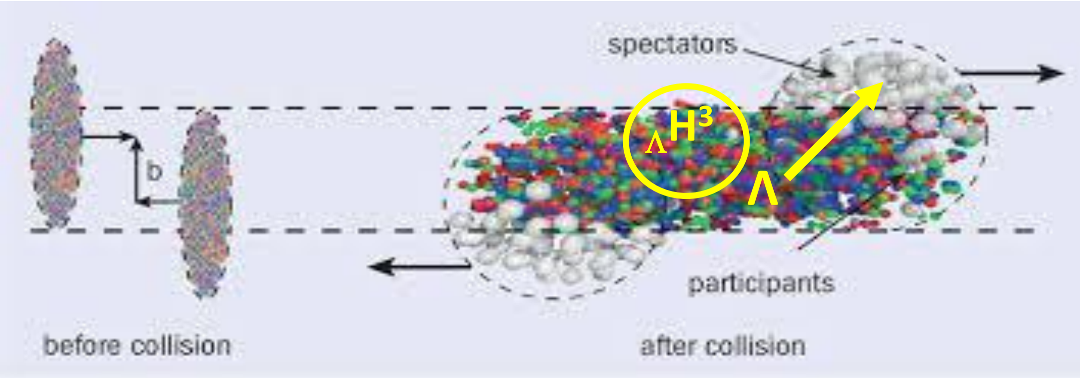
How to use heavy ion reactions to study the nuclear EOS?



Strategy:

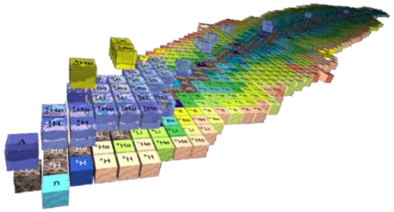
- develop transport approaches
  which simulate the transport of strongly interacting particles
  (Quantum Molecular Dynamics, Boltzmann Ühling Uhlenbeck)
- vary EoS in the simulation
- identify observables which are sensitive to the EOS
- compare experimental measurements with theory

What can we study with transport approaches ?



elementary strangeness production mechanism:
In HI collisions strangeness can be produced differently than in NN collisions (three body reaction)

in medium properties of (strange) hadrons and Λ(K)N potential
(test of the theoretical predictions, -> neutron stars?)



the reaction dynamics
(midrapidity particles come exclusively from the participant zone -> elliptic flow)

transition to the quark gluon plasma and its properties
(different T_c for strange and nonstrange hadrons?)

Agreement between exp. results and all these theor. predictions assures validity of transport

Quantum Molecular Dynamics (QMD)

Time dependent Ritz variational principle (Koonin, TDHF)

Take trial wavefct with time dependent parameters and solve

$$\delta \int_{t_1}^{t_2} dt < \psi(t)| i\frac{d}{dt} - H|\psi(t) >= 0. \qquad (1)$$

QMD trial wavefct for particle i with p_{oi} (t) and q_{oi} (t)

$$\psi_i(q_i, q_{0i}, p_{0i}) = C exp[-(q_i - q_{0i} - \frac{p_{0i}}{m}t)^2/4L] \cdot exp[ip_{0i}(q_i - q_{0i}) - i\frac{p_{oi}^2}{2m}t]$$

For N particles: $\psi_N = \prod_{i=1}^{N} \psi_i(q_i, q_{0i}, p_{0i})$ QMD

For the QMD trial wavefct eq. (1) yields

$$\frac{dq}{dt} = \frac{\partial < H >}{\partial p} \quad ; \quad \frac{dp}{dt} = -\frac{\partial < H >}{\partial q}$$

For Gaussian wavefct
eq. of motion very similar
to Hamilton's eqs.
(but only for Gaussians !!)

Quantum Molecular Dynamics (QMD) II

- nucleon-nucleon density dependent two body potential:

$$
\begin{aligned}
V^{ij} &= G^{ij} + V^{ij}_{\mathrm{Coul}} \\
&= V^{ij}_{\mathrm{Skyrme}} + V^{ij}_{\mathrm{Yuk}} + V^{ij}_{\mathrm{mdi}} + V^{ij}_{\mathrm{Coul}} + V^{ij}_{sym} \\
&= t_1 \delta(\vec{x}_i - \vec{x}_j) + t_2 \delta(\vec{x}_i - \vec{x}_j) \rho^{\gamma-1}(\vec{x}_i) + t_3 \frac{\exp\{-|\vec{x}_i - \vec{x}_j|/\mu\}}{|\vec{x}_i - \vec{x}_j|/\mu} + \\
&\quad t_4 \ln^2(1 + t_5(\vec{p}_i - \vec{p}_j)^2)\delta(\vec{x}_i - \vec{x}_j) + \frac{Z_i Z_j e^2}{|\vec{x}_i - \vec{x}_j|} + \\
&\quad t_6 \frac{1}{\varrho_0} T_3^i T_3^j \delta(\vec{r}_i - \vec{r}_j)
\end{aligned}
$$

t_1 - t_3 depend on the EoS

t_4 contains the momentum dependence of the potential

- In addition all necessary cross sections and decays:

  like NN elastic, NN←→NΔ, Δ→Nπ

Strange hadrons as a tool to study the
nuclear reaction dynamics
and the nuclear equation of state
up to densities of $3\rho_0$

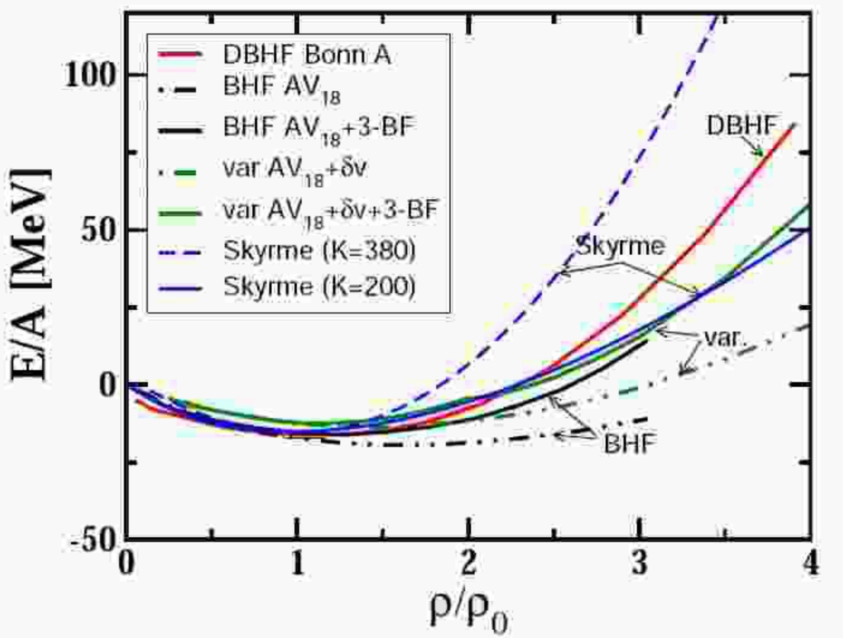
EoS from fundamental theories

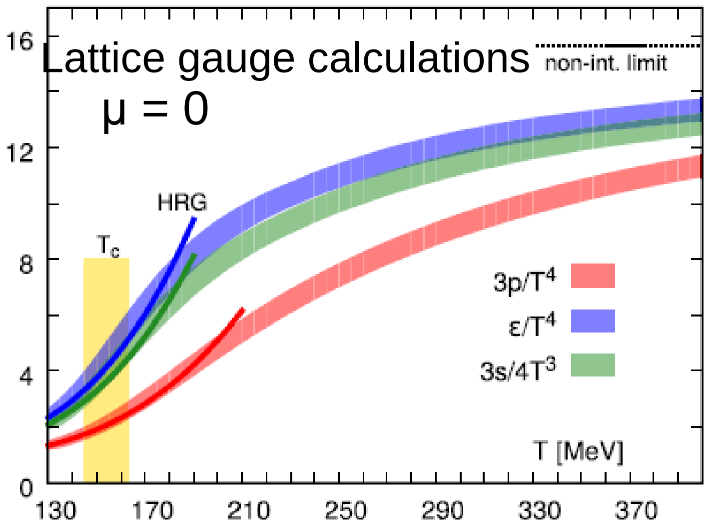
theory based on fundamental interactions is limited to

low temperature and $\rho < 1.5 - 2\rho_0$
Brückner G –matrix
(hole line expansion)

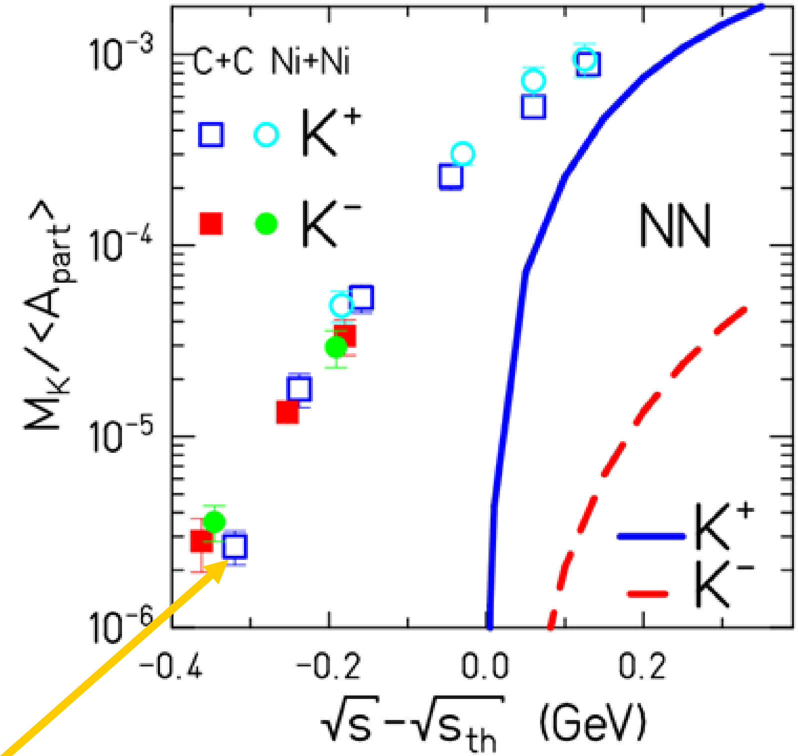
high temperatures and $\mu \approx 0$
lattice gauge calculations

At low energies E/A(T,ρ) instead P(T,ρ(μ)) or ε(T,ρ(μ))





Strangeness and the nuclear equation of state



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

- NN: Excitation function of K^+ and K^- quite different
- AA: Excitation function of K^+ and K^- quite similar
- Fermi motion cannot explain very subthreshold production

- Conclusion
  AA: new mechanisms for strangeness production

(C. Hartnack et al., Phys. Rept. 510,119)

Near threshold strangeness production in AA

I. Strangeness production channels at low energies

baryon-baryon collisions:

$$B+B \rightarrow B+Y+K$$

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

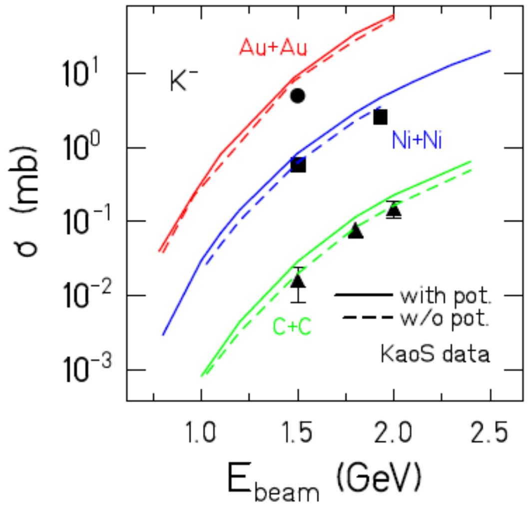
$$B+Y \rightarrow B+B+\overline{K}$$

$K=(K,K^0)$

$\overline{K}=(K^-,\overline{K}^0)$

$B=(N,\Delta,...)$

$Y=(\Lambda,\Sigma)$



meson-baryon collisions:

$$\pi+B \rightarrow Y+K$$

$$\pi+B \rightarrow B+K+\overline{K}$$

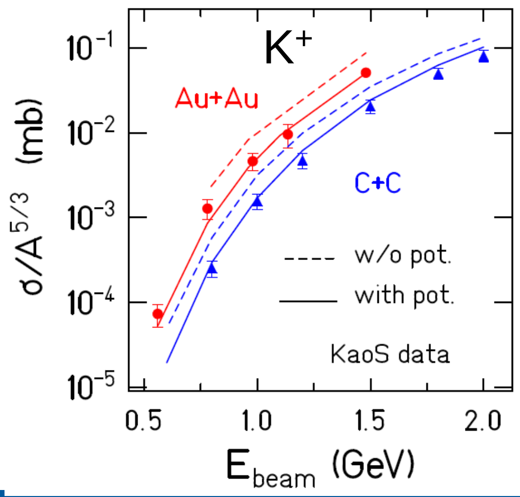
$$\pi+Y \rightarrow B+\overline{K}$$

→ dominant channel for low energy K^- production!

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

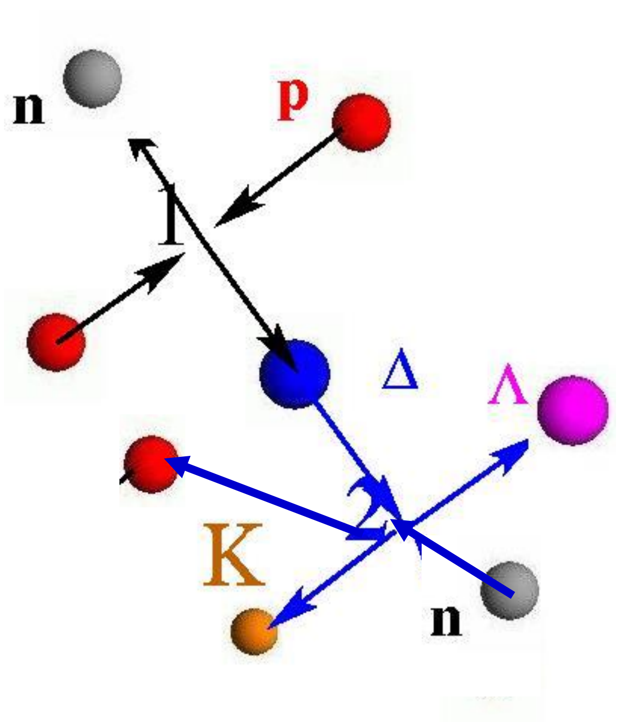
II. Strangeness rescattering
= (quasi-)elastic scattering with baryons and mesons

III. K^+ (K^-)-Nucleus potential $V(\rho)$



Origin of difference of pp and AA excitation functions

Dominant for K^+ in AA: Two step process NN→NΔ NΔ→K^+Λ N



lowers the effective threshold

enhances K^+ below NN threshold

two step process more probable in central collision

Theory and simulations:

soft EoS: system gets to higher densities

→ shorter mean free path for NΔ→K^+Λ N

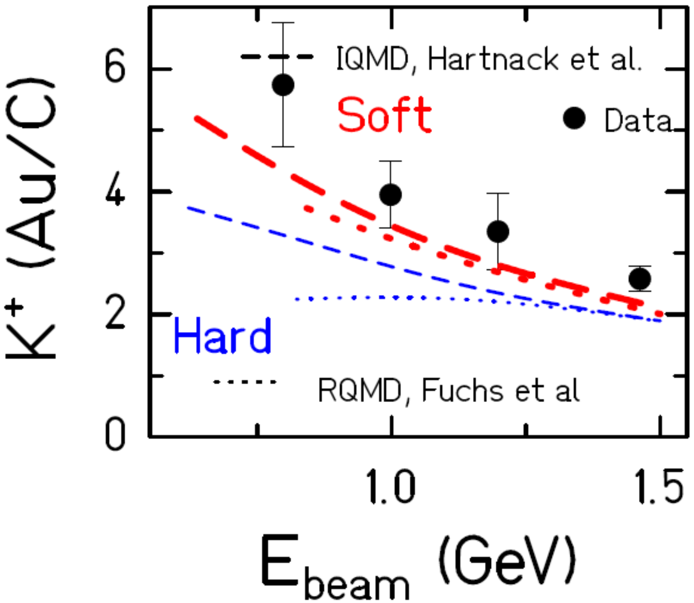
NΔ→ K^+Λ N competes with Δ decay

→ for a soft EOS we expect more NΔ→K^+Λ N collisions

and hence more K^+

Strangeness production and the nuclear EoS

(Phys. Rept. 510,119)



Comparison with experiment

- confirmes the EoS dependence of K^+ yield
- soft EoS: best agreement with data

Up to today the observable
which shows the strongest EoS dependence

- Perspectives: FAIR and NICA (Russia) have higher beam energies
  excitation functions of Ξ and Ω become available
  sensitive probes for studying the reaction mechanism and EoS

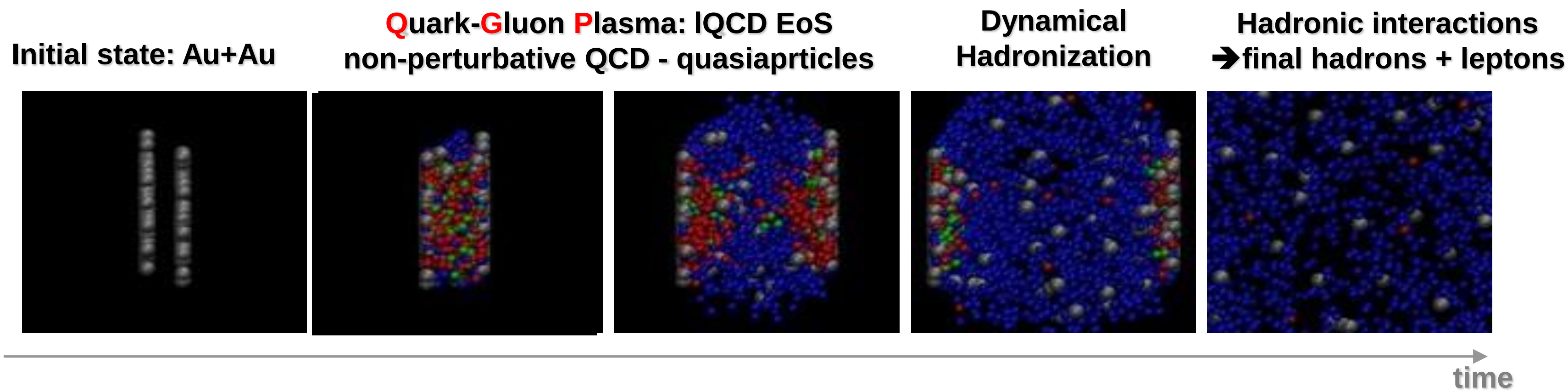
The modification of strange hadrons
by the nuclear environment

PHSD

the transport approach to study off-shell dynamics

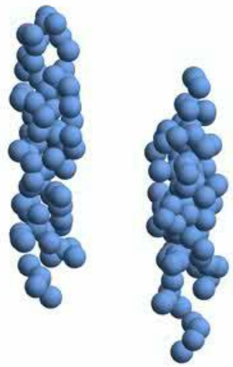
Parton-Hadron-String Dynamics (PHSD) is a non-equilibrium microscopic transport approach for the description of strongly-interacting hadronic and partonic matter created in heavy-ion collisions

Dynamics: based on the solution of generalized off-shell transport equations derived from Kadanoff-Baym many-body theory



➔ PHSD provides a good description of 'bulk' hadronic observables as well as of dilepton spectra from SIS to LHC energies

PHSD: W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; W. Cassing, EPJ ST 168 (2009) 3 t = 0.05 fm/c



Au+Au @ 35 AGeV

b = 2.2 fm – Section view

- Baryons (395)
- Antibaryons (0)
- Mesons (0)
- Quarks (0)
- Gluons (0)

P.Moreau

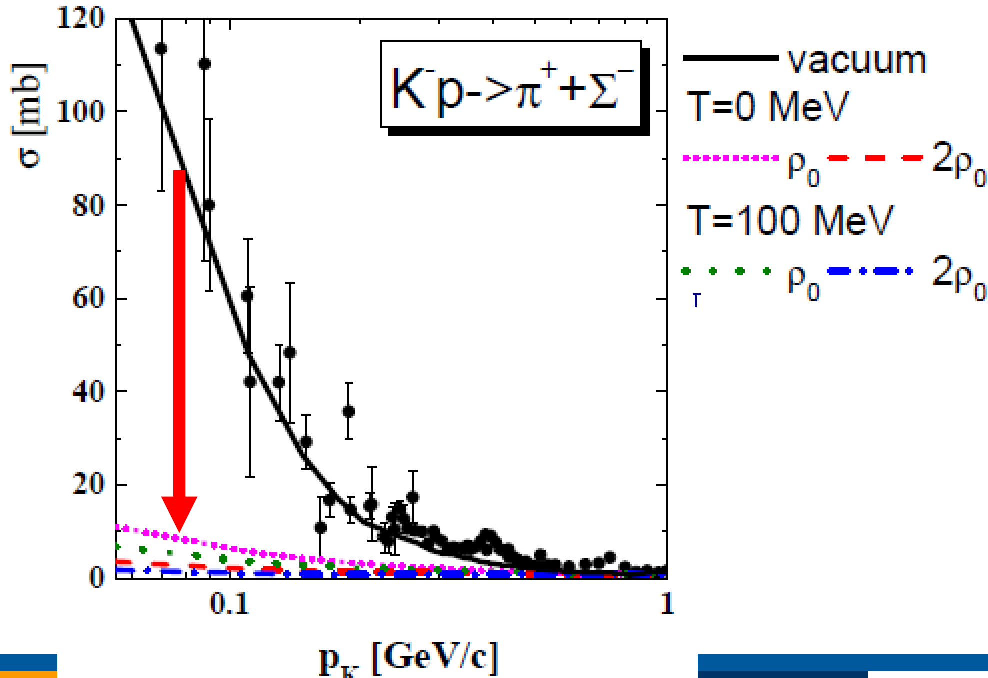
Hadrons in an hadronic environment – all but simple

Hadrons in an hadronic environment -> interaction among the hadrons
Chiral perturbation theory based on SU(3) baryon-meson chiral Lagrangian
(here including s- and p- waves) which is also used for NS studies

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

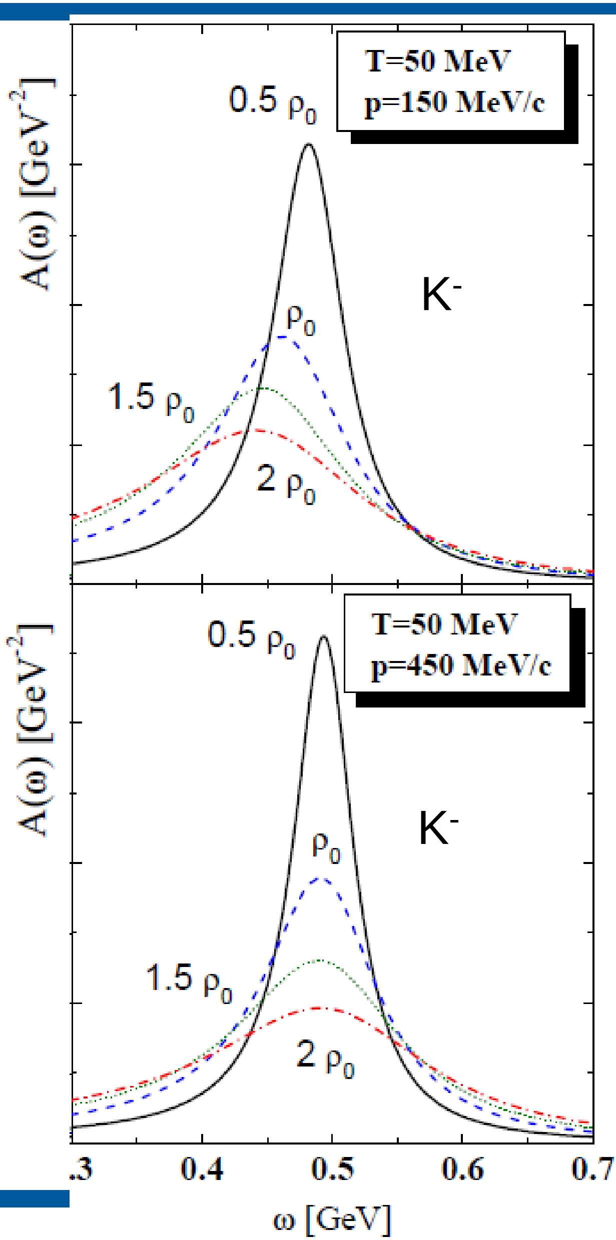
B = baryon field
M = meson field

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



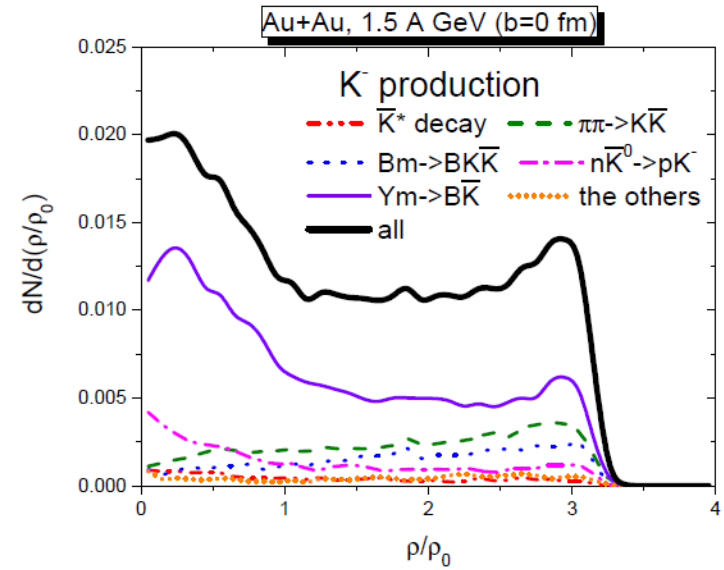
Details: PRC103,044901

Spectral function and environment at creation

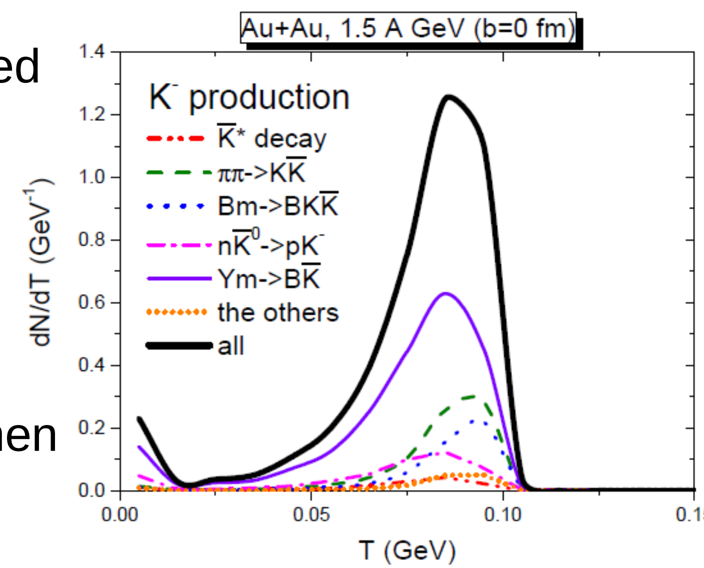


Spectral function broader with increasing density

mass shift for low momentum hadrons



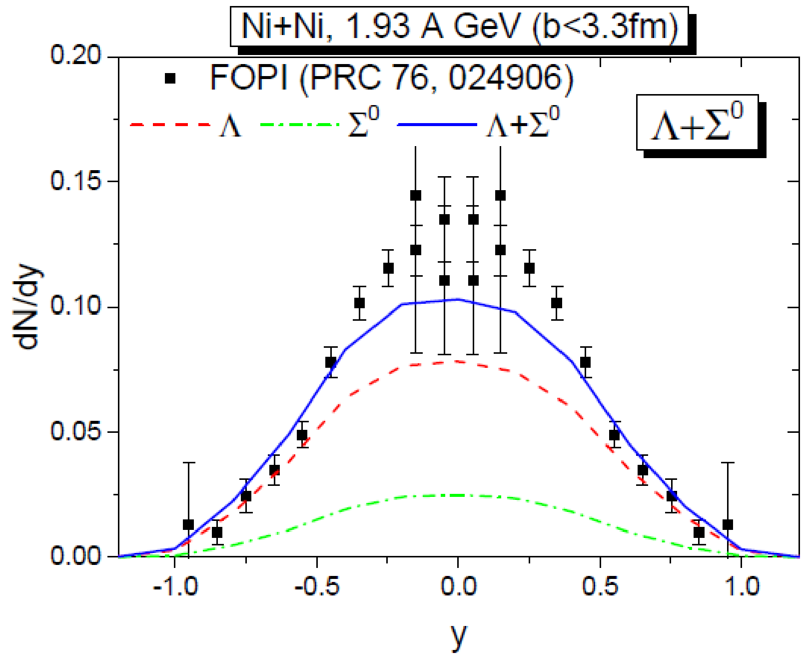
Most K are produced at high T and ρ

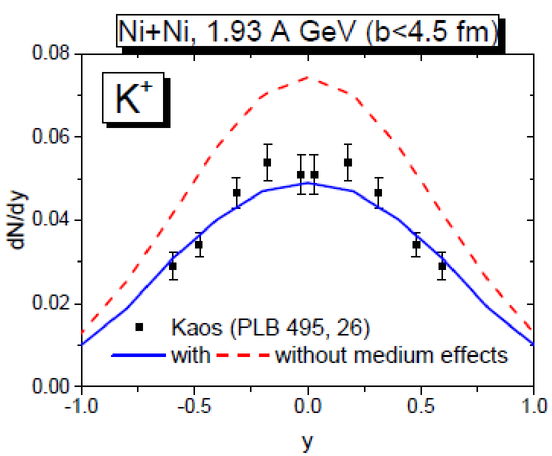


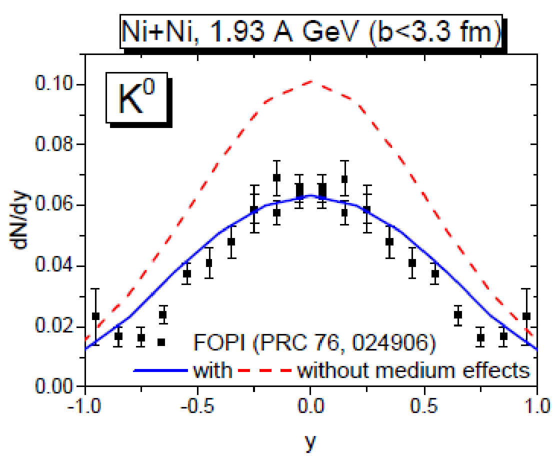
→ Strong modification of particles properties when they are produced

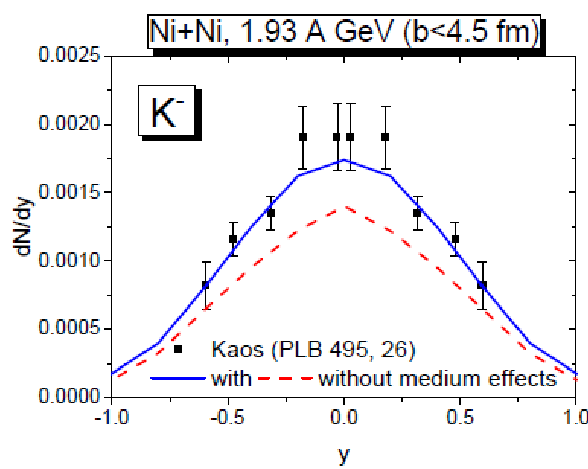
Consequences for the observables

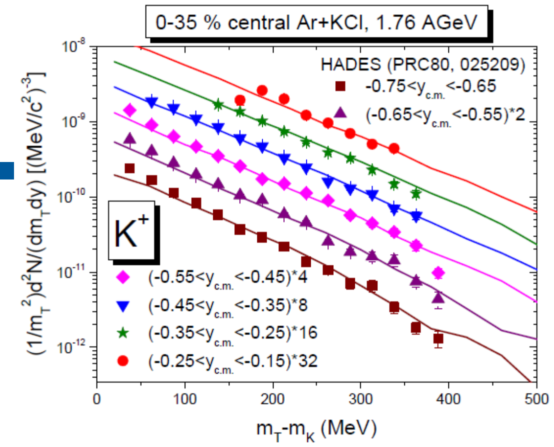
The interaction of hadrons at their creation point (and later) with the environment changes multiplicity, rapidity distribution and p_T spectra.



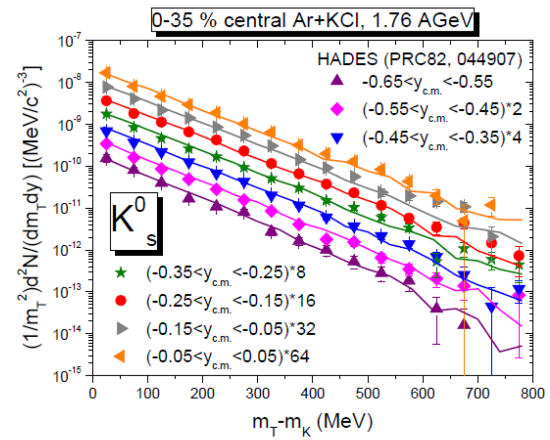








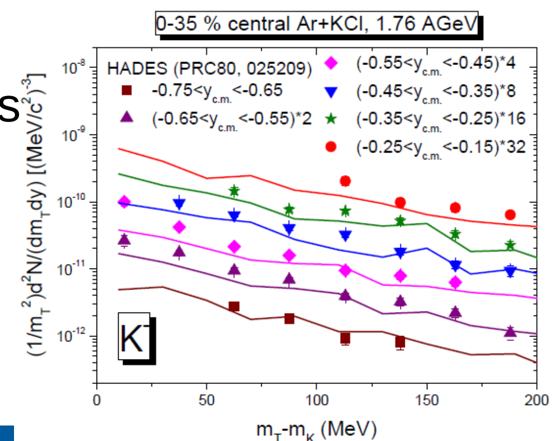
as well as the p_T spectra



Consequence: theoretical medium modification of strange particle properties confirmed by experiment.

They can be used to determine the EoS dependence of particle properties

and reduce the present uncertainties in the models of astrophysical and gravitational wave studies



Conclusions

The nuclear equation of state (EOS) of strongly interacting matter is needed for several problems

- the physics in the interior of neutron stars
- to understand the transition between Quark Gluon Plasma and Hadrons
- to interpret gravitational wave

Very complicated issue $\mu \neq 0$ problem for lattice
breakdown of the many body schema

Experimental results may help

K^+ yield is sensitive to the nuclear EOS at $\rho \approx$ 2-3 ρ_0

Strange particles properties and cross sections are sensitive to T and ρ of the nuclear environment change their spectral function and their masses

Future experiments at NICA and FAIR may allow for more information and reduce the uncertainties for neutron star and gravitational wave studies

Thank you