Heavy Hadrons under Extreme Conditions

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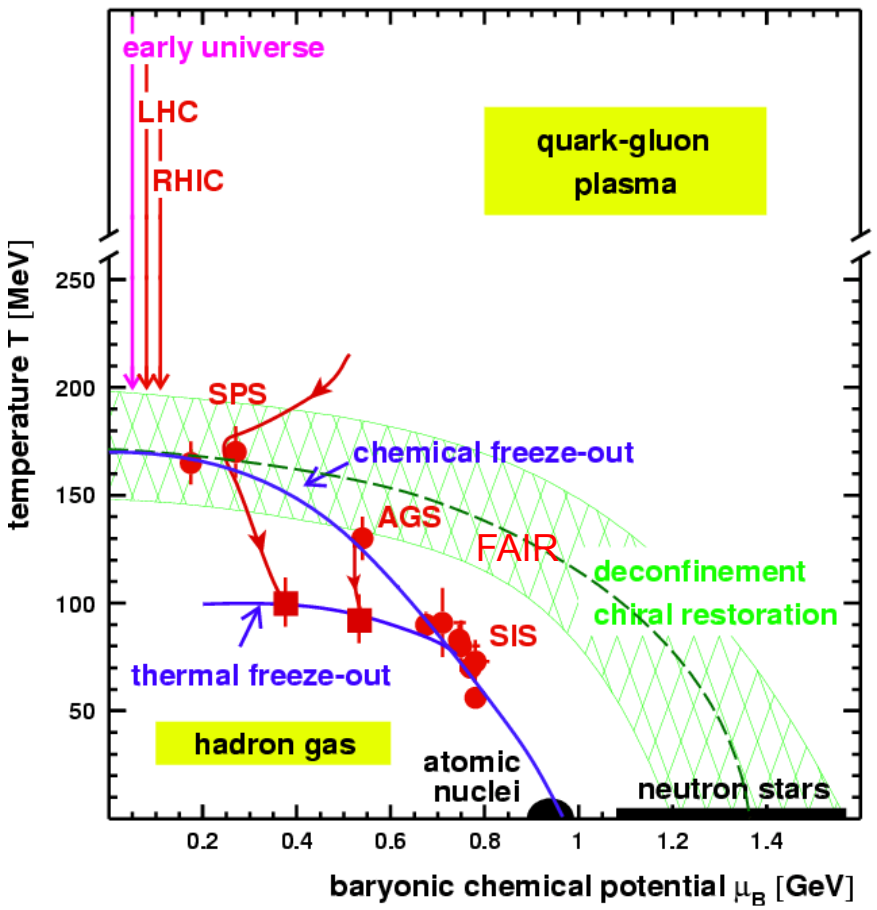
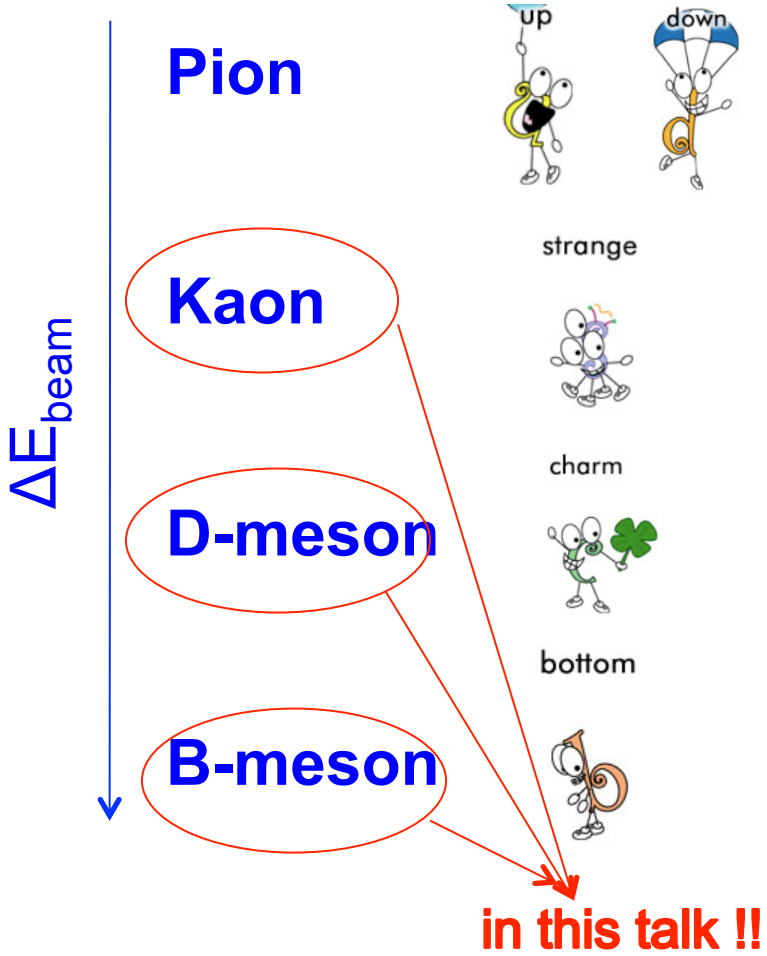
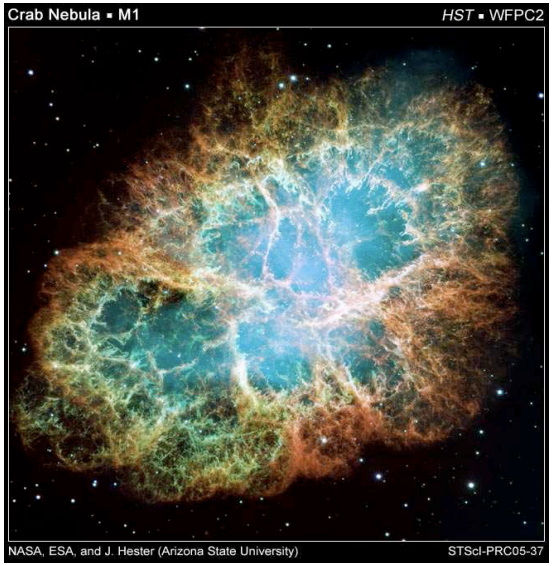
Understand matter under extreme conditions

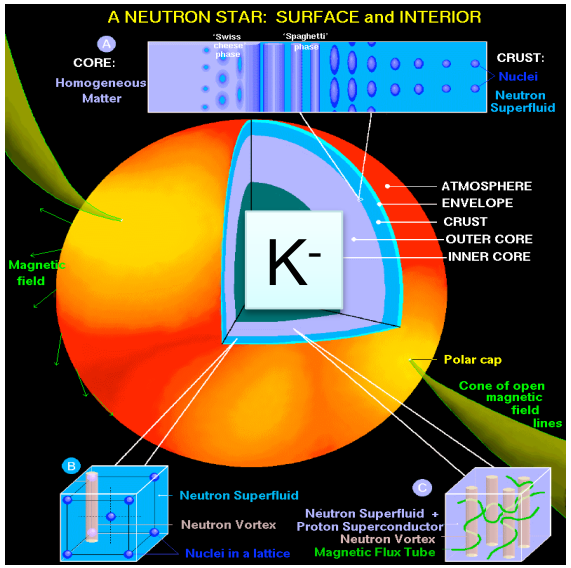


NuPECC report



Strangeness under Extreme Conditions



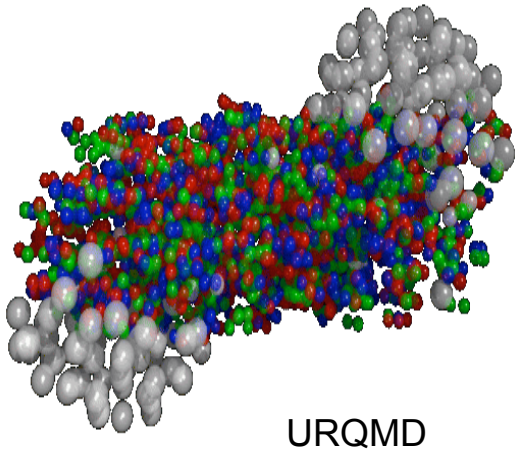


Kaon condensation in neutron stars

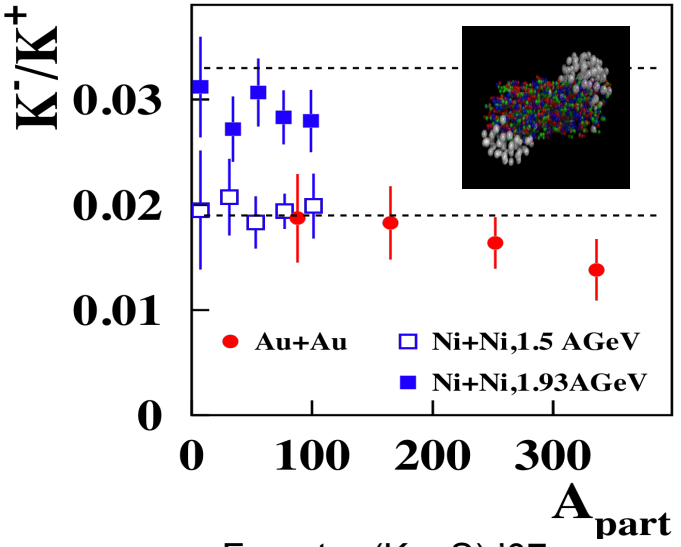
Kaplan and Nelson ’86 ...

In the laboratory

Crochet et al (FOPI)’00
Wisniewski et al (FOPI) ’00
Foerster et al (KaoS) ‘07
Salabura ‘12 (HADES)
CBM (FAIR) Physics Book ’11..



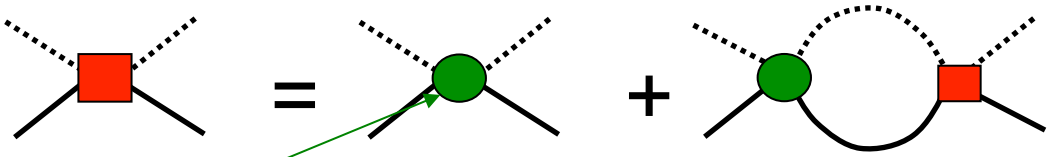
URQMD



Foerster (KaoS) ’07

Unitarized theory in matter:
selfconsistent coupled-channel procedure

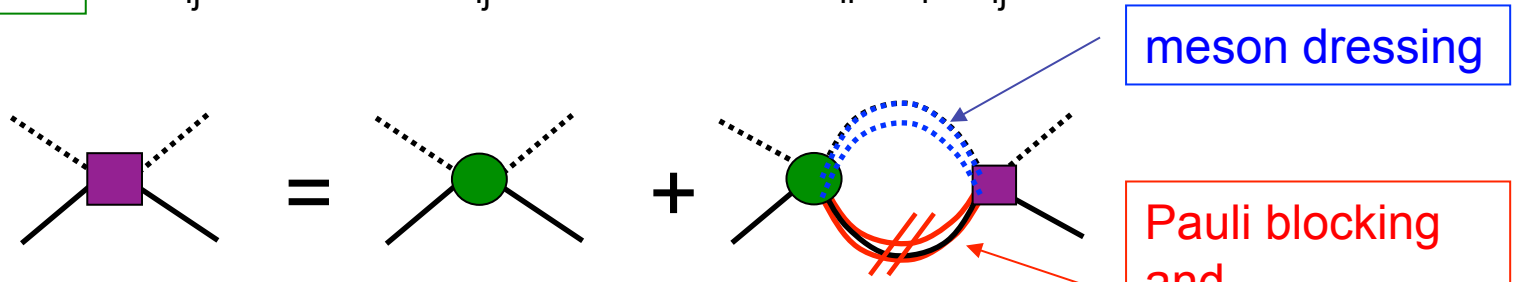
Free space



potential from LO chiral Lagrangian

$$T_{ij} = V_{ij} + V_{il}\, G_l\, T_{lj}$$

Medium



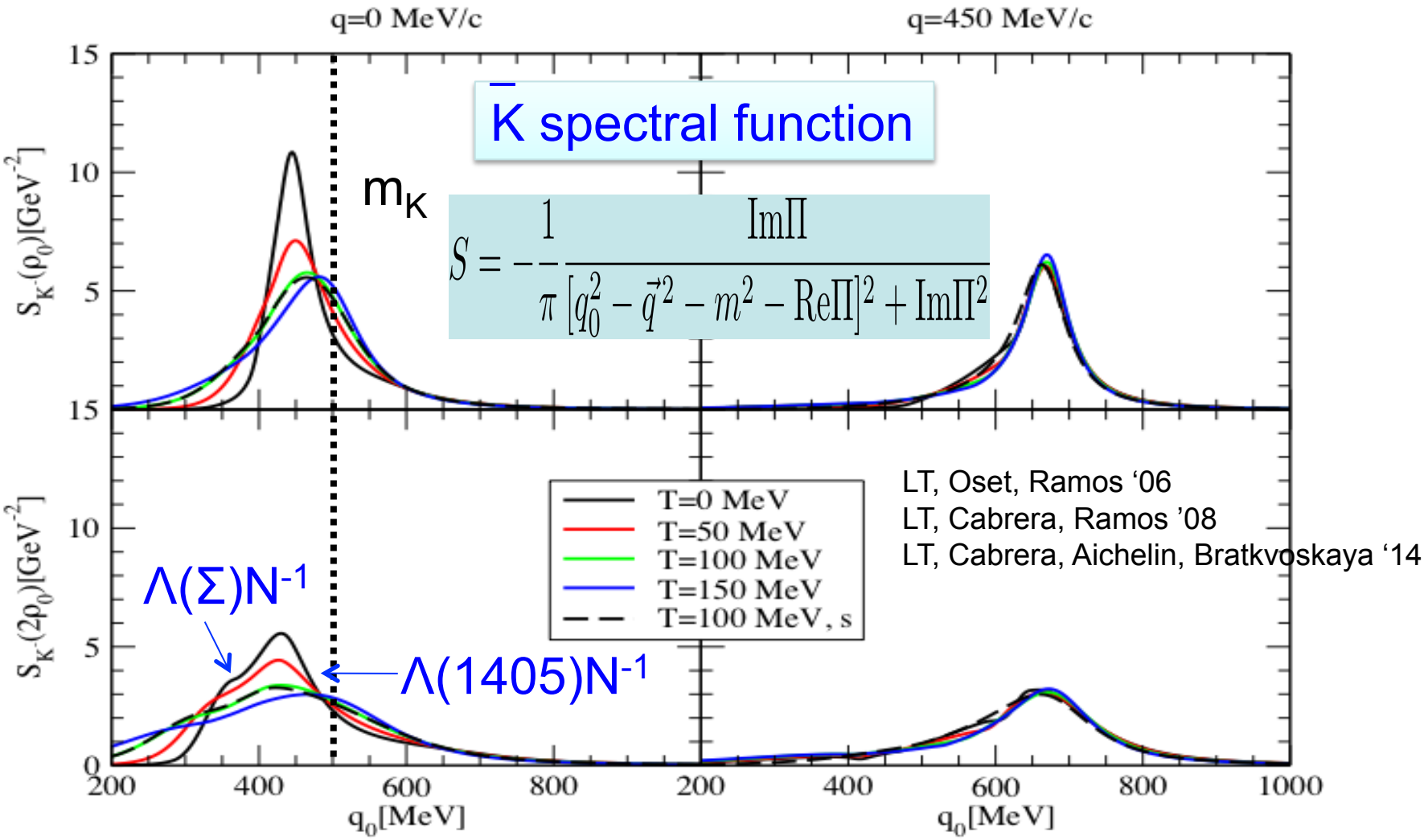
$$T_{ij}(\rho,T) = V_{ij} + V_{il}\, G_l(\rho,T)\, T_{lj}(\rho,T)$$

Dressed meson:

Π self-energy

Unitarized theory in matter: selfconsistent coupled-channel procedure

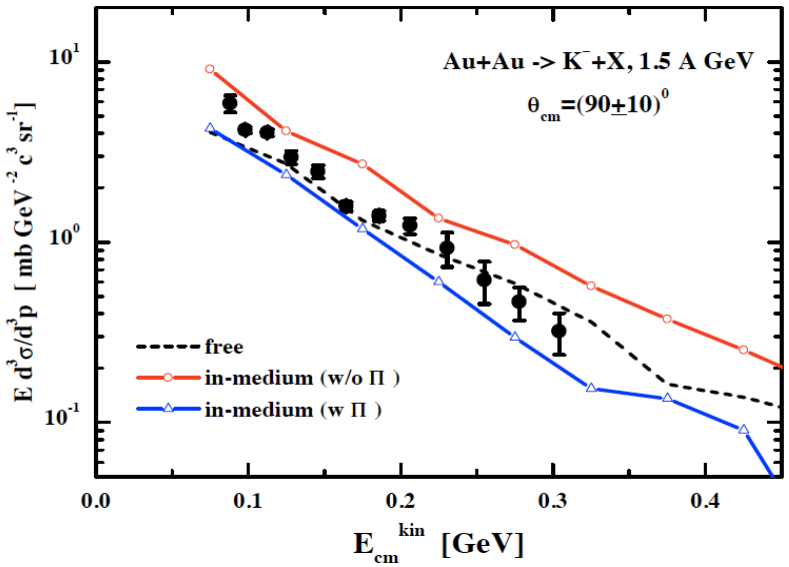
Koch '94; Waas and Weise '97; Kaiser et al '97; Oset and Ramos'98; Lutz '98; Schaffner-Bielich et al '00; Ramos and Oset '00; Lutz et al '02 ; LT et al '01 '02; Jido et al '02 '03; Magas et al '05; LT et al '06 '08; Lutz et al '08

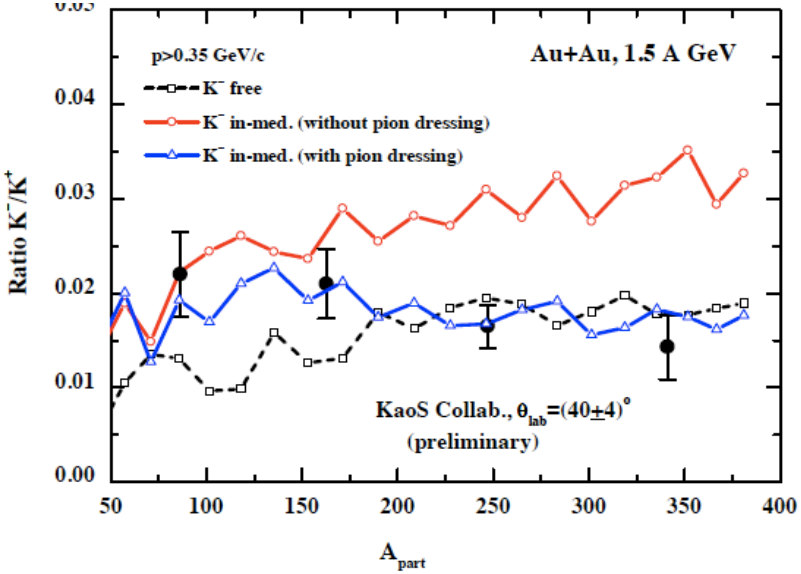


LT, Oset, Ramos '06
LT, Cabrera, Ramos '08
LT, Cabrera, Aichelin, Bratkvoskaya '14

Strangeness production in heavy-ion collisions

Recent report on strangeness production close to threshold in proton-nucleus and heavy-ion collisions Hartnack et al. '12





First attempts to describe
all data simultaneously with full spectral features of strange mesons

Cassing, LT, Bratkovskaya and Ramos '03

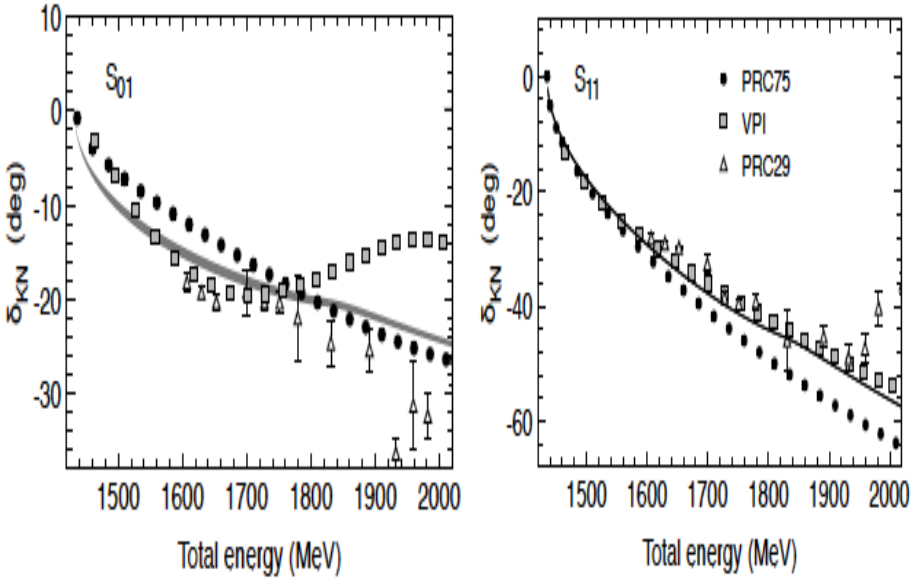
Collaboration ICE-FIAS-SUBATECH:
Working on implementing the properties of strange mesons in dense hot matter coming from chiral effective theory in an off-shell transport model for heavy-ion collisions

Recent results on strangeness +1 KN - K*N systems

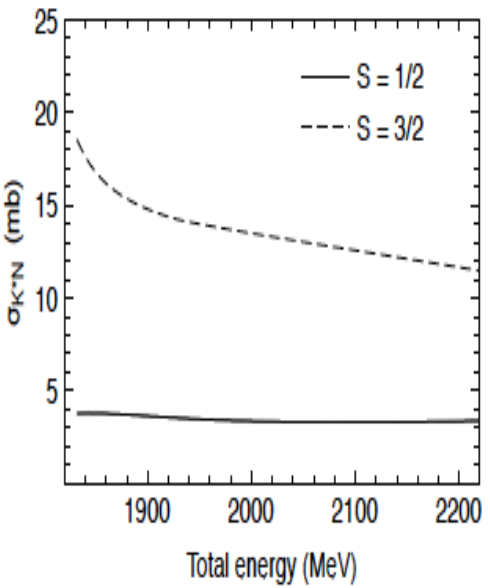
Khemchandani, Martinez-Torres, Navarra, Nielsen and LT '14

Potential for
KN : LO chiral Lagrangian
K*N : s-,t-,u- channels and contact term from hidden gauge formalism
KN-K*N : extension of Kroll-Ruderman term

We fit subtraction constants
to KN I=0 and I=1 phase shifts



We predict KN and K*N cross sections,
and K*N scattering lengths



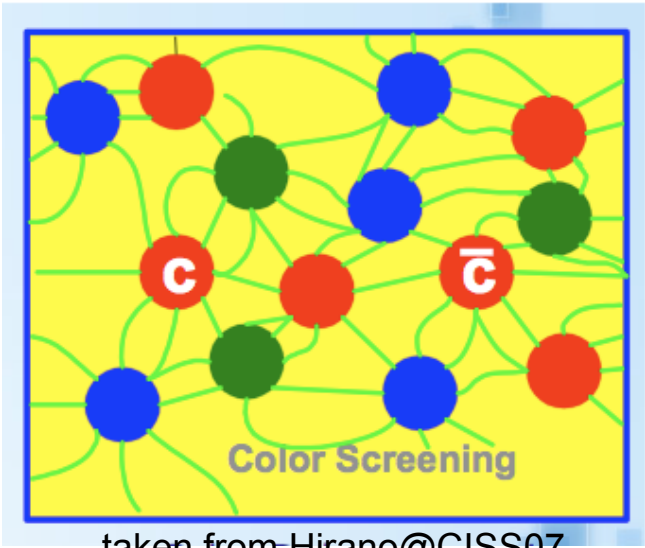
$a^{I,S}_{K^*N}$ (fm)
$I=0,\ S=1/2$
(0.2,0.03)
$I=0,\ S=3/2$
(-0.08,0.04)
$I=1,\ S=1/2$
(0.1,0.0)
$I=1,\ S=3/2$
(-0.31,0.03)

Results of special interest from K* production in p+p and p+A collisions
@ HADES, STAR and NA49

Charm under Extreme Conditions

J/Ψ suppression

Gonin et al (NA50) ’96, Matsui and Satz ’86



taken from Hirano@CISS07

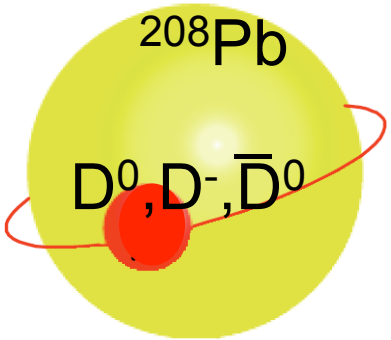
but also comover scattering

$$J/\Psi + \pi \rightarrow D + \bar{D}$$

Capella, Ferreiro, Vogt, Wang, Bratkovskaya, Cassing, Andronic..

D-mesic nuclei

Tsushima et al ’99,
Garcia-Recio et al ’10
Garcia-Recio et al ’12
Yasui et al ’12..



Meson-baryon interaction with heavy quarks: Incorporate Heavy-Quark Spin Symmetry

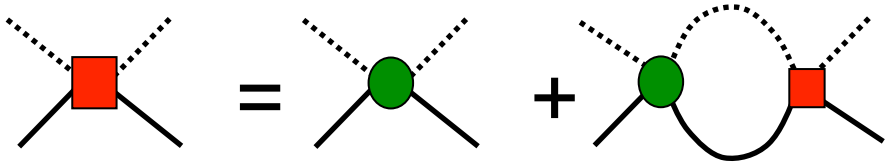
HQSS*: spin interactions vanish for infinitely massive quarks

*Isgur, Wise, Manohar, Neubert

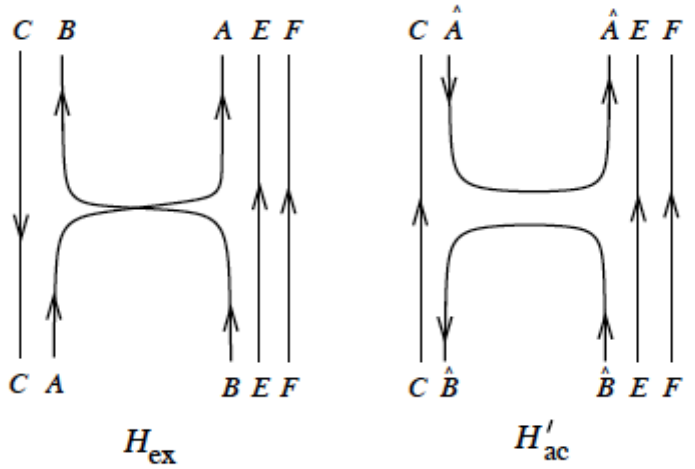
To construct a model for four flavors for pseudoscalar and vector mesons as well as $1/2^+$ and $3/2^+$ baryons that incorporates HQSS in the charm sector: extended WT interaction that fulfills SU(6)xHQSS and it is consistent with chiral symmetry in the light sector

$$V = \frac{K(s)}{4f^2} H'_{\rm WT}, \qquad H'_{\rm WT} = H_{\rm ex} + H'_{\rm ac}.$$

K(s): depends on meson-baryon energy
f: decay constant



$T_{ij} = V_{ij} + V_{il}\, G_l\, T_{lj}$



$H_{\rm ex}$ $\qquad$ $H'_{\rm ac}$

H_{ex}: exchange of quarks
H'_{ac}: annhilation and creation of quark-antiquark pairs, corrected with HQSS constraints (only light quarks)

Spectroscopy of excited charmed baryons

Λ_c : C=1,S=0,I=0

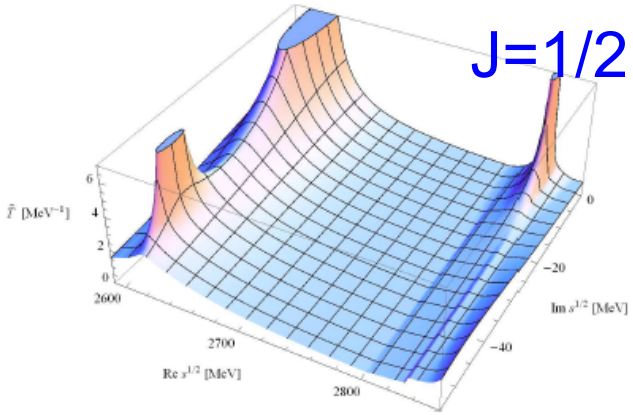
Garcia-Recio et al.'09;
Romanets et al. '12

$$T_{ij}(s) \approx \frac{g_i g_j}{\sqrt{s} - \sqrt{s_R}}$$

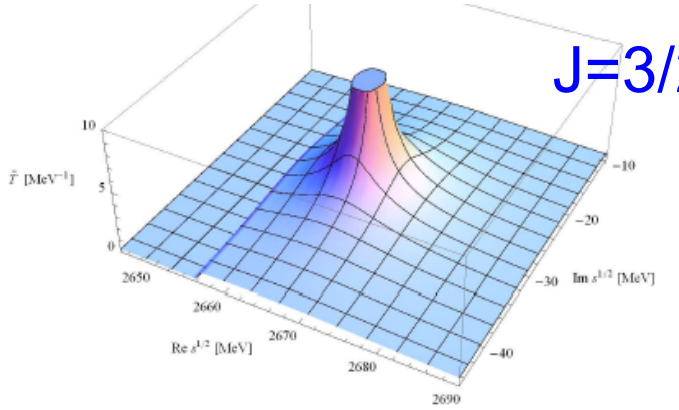
coupling constant

mass and width

J=1/2



J=3/2



SU(8) irrep	SU(6) irrep	SU(3) irrep	M_R	Γ_R	Couplings to main channels	Status PDG	J
168	$\mathbf{15}_{2,1}$	$\mathbf{3}^*_2$	2617.3	89.8	$g_{\Sigma_c\pi} = \mathbf{2.3}$, $g_{ND} = 1.6$, $g_{ND^*} = 1.4$, $g_{\Sigma_c\rho} = 1.3$		1/2
168	$\mathbf{15}_{2,1}$	$\mathbf{3}^*_4$	2666.6	53.7	$g_{\Sigma_c^*\pi} = \mathbf{2.2}$, $g_{ND^*} = 2.0$, $g_{\Sigma_c\rho} = 0.8$, $g_{\Sigma_c^*\rho} = 1.3$	$\Lambda_c(2625)$ ***	3/2
168	$\mathbf{21}_{2,1}$	$\mathbf{3}^*_2$	2618.8	1.2	$g_{\Sigma_c\pi} = \mathbf{0.2}$, $g_{ND} = 3.5$, $g_{ND^*} = 5.6$, $g_{\Lambda D_s} = 1.4$, $g_{\Lambda D_s^*} = 2.9$, $g_{\Lambda_c\eta} = 0.9$	$\Lambda_c(2595)$ ***	1/2
120	$\mathbf{21}_{2,1}$	$\mathbf{3}^*_2$	2828.4	0.8	$g_{ND} = \mathbf{0.3}$, $g_{\Lambda_c\eta} = 1.1$, $g_{\Xi_c K} = 1.6$, $g_{\Lambda D_s^*} = 1.1$, $g_{\Sigma_c\rho} = 1.1$, $g_{\Sigma_c^*\rho} = 1.0$, $g_{\Xi_c^* K^*} = 0.8$		1/2

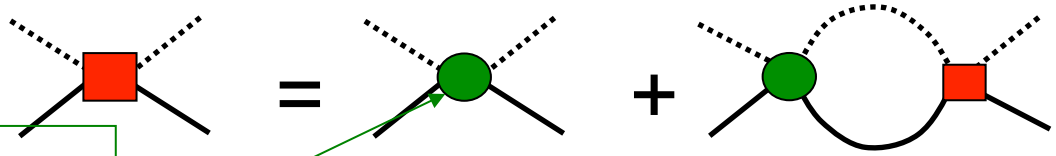
- $\Lambda_c(2595)$ has large DN and D*N components
- Double-pole pattern for $\Lambda_c(2595)$, like for $\Lambda(1405)$
- Identification of $\Lambda_c(2625)$

Charmed hadrons in matter

Unitarized theory in matter:

selfconsistent coupled-channel procedure

Free space

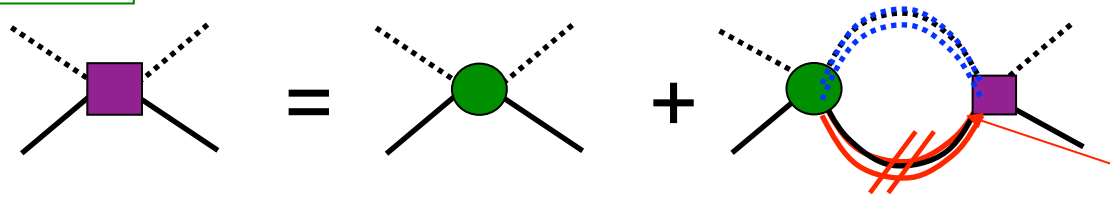


potential from extended WT interaction that respect HQSS

$T_{ij} = V_{ij} + V_{il}\ G_l\ T_{lj}$

meson dressing

Medium



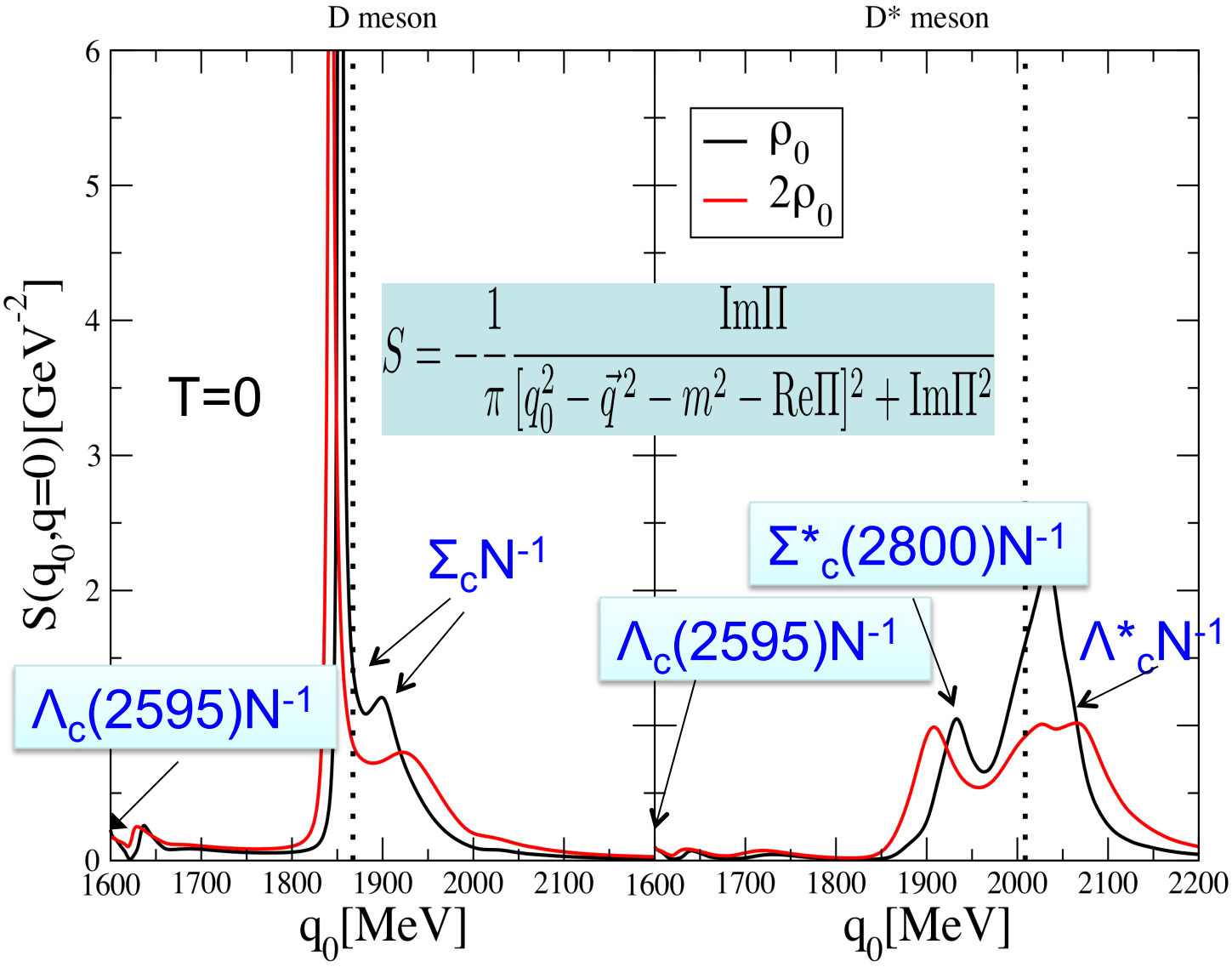
Pauli blocking and baryon dressing

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

Dressed meson:

Π self-energy

Unitarized theory in matter:
selfconsistent coupled-channel procedure



Simultaneous calculation of D and D* self-energies

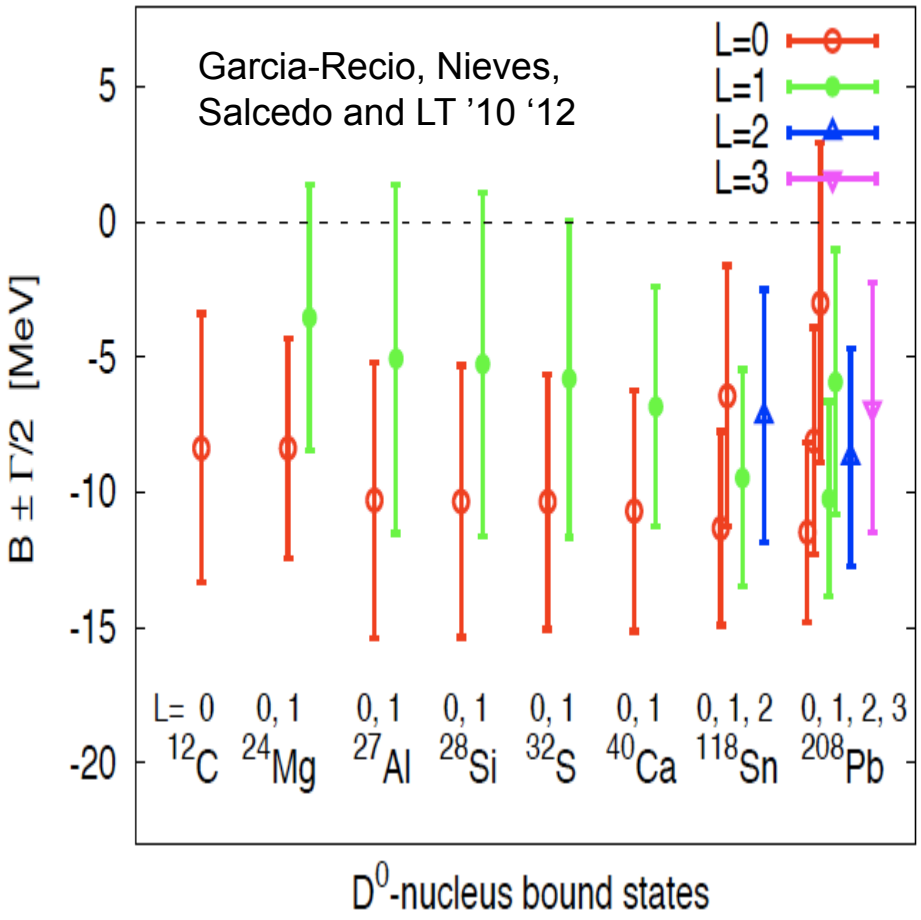
Garcia-Recio et al '09
LT et al. '10;
Gamermann et al. '10
Garcia-Recio et al. '10
Garcia-Recio et al.'12
Romanets et al. '12
Garcia-Recio et al. '13
Garcia-Recio et al. '13

D mesons in nuclei

Solving Schroedinger equation...

$$V_D(r,E) = \frac{\Pi_D(q^0 = m_D + E, \vec{q} = 0, \rho(r))}{2m_D}$$
$$E = q^0 - m_D$$

$$\left[-\frac{\nabla^2}{2m_{\rm red}} + V_{\rm coul}(r) + V_{\rm opt}(r)\right]\Psi = (-B - i\Gamma/2)\Psi$$



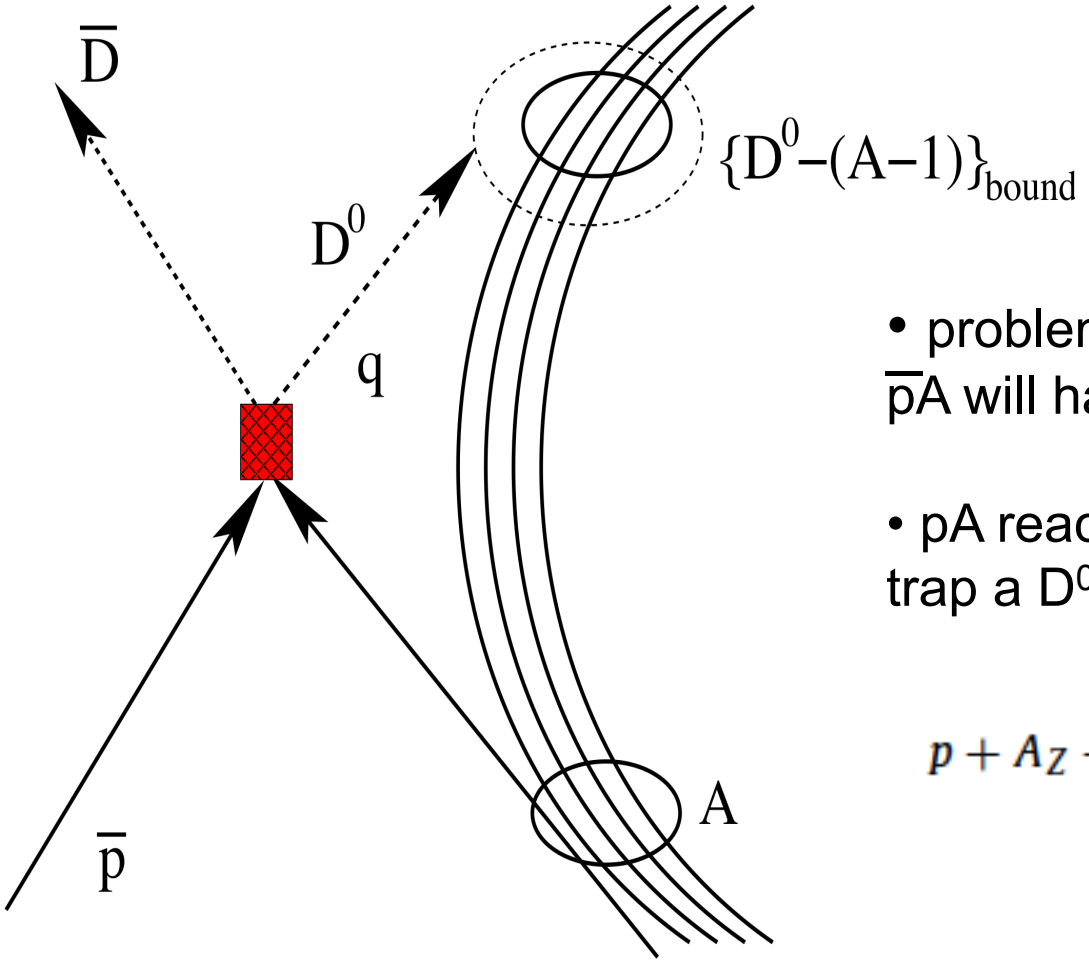
- Weakly bound D^0-nucleus states with important widths in contrast to QMC model.

Tsushima et al. '99

State	$D^0(V_\omega^q)$
$1s$	-96.2
$1p$	-93.0
$2s$	-88.5

- D^+ does not bind
- D^- and D^0 bind in nuclei

Experimental observation is, though, a difficult task



- problem at PANDA@FAIR:
$\overline{p}A$ will have a low production rate

- pA reaction seems more likely to trap a D^0 in nuclei

$$p + A_Z \rightarrow p + \bar{D}^0 + \underbrace{\{A_Z - D^0\}_{\text{bound}}}_{\hookrightarrow\ \Lambda_c\pi + X,\ \Sigma_c\pi + X} .$$

D meson propagation in dense hot matter

D-mesons: One of the cleanest probes of the early stages of the collision

Their relaxation time is long enough to not fully thermalize, but short enough to undergo significant reinteractions which reflect on their coupling to the medium.

$$\tau_{rel}^{H} \sim \frac{M}{T}\,\tau_{rel}^{light}\ ; \qquad \frac{M}{T} \sim 6-20$$

Teaney and Moore '05

The D meson propagation can be studied using a kinetic description for the distribution function.

Given that $m_D >> m_{light}$

$$\frac{\partial f(t,\mathbf{p})}{\partial t} = \frac{\partial}{\partial p_i}\left\{F_i(\mathbf{p}) f(t,\mathbf{p}) + \frac{\partial}{\partial p_j}\left[\Gamma_{ij}(\mathbf{p}) f(t,\mathbf{p})\right]\right\},$$

drag force — diffusion coefficient

Fokker-Planck equation

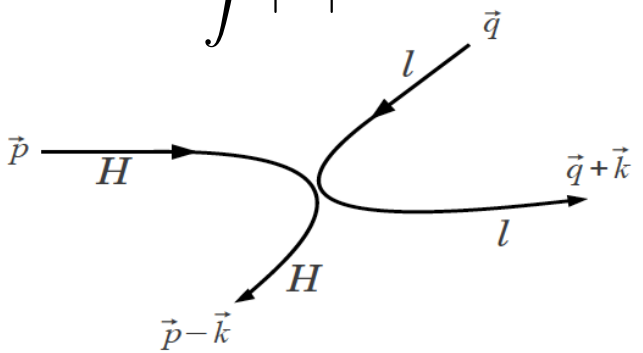
For an isotropic bath

$$F(p) = \int d\mathbf{k} w(\mathbf{p}, \mathbf{k}) \frac{k_i p^i}{p^2},$$

$$\Gamma_0(p) = \frac{1}{4} \int d\mathbf{k} w(\mathbf{p}, \mathbf{k}) \left[\mathbf{k}^2 - \frac{(k_i p^i)^2}{p^2} \right],$$

$$\Gamma_1(p) = \frac{1}{2} \int d\mathbf{k} w(\mathbf{p}, \mathbf{k}) \frac{(k_i p^i)^2}{p^2},$$

$$\omega \propto \int |T|^2 d\Omega$$



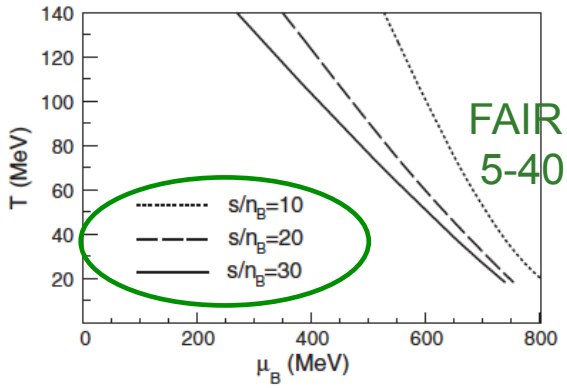
We need scattering amplitudes $|T|^2$

Previous works on D-meson propagation with different models for $|T|^2$
Laine ‘11; He, Fries, Rapp ‘11; Ghosh, Das, Sarkar, -eAlam ’11

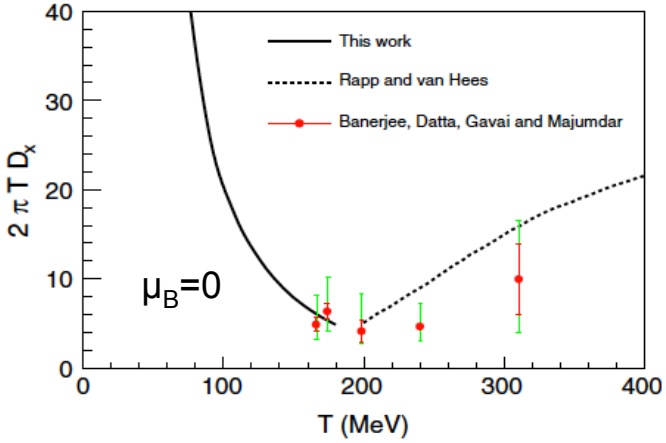
We use $|T|^2$ from unitarized model in matter based on effective theories for meson-meson and meson-baryon interactions that respect HQSS
Abreu, Cabrera, Llanes-Estrada, Torres-Rincon ’11; LT and Torres-Rincon ’13

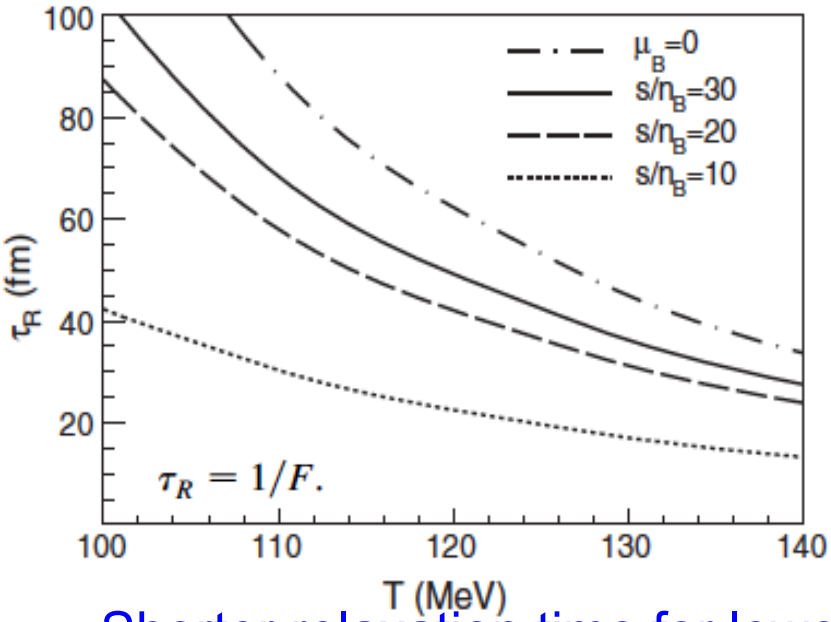
Some results for FAIR energies

LT and Torres-Rincon '13

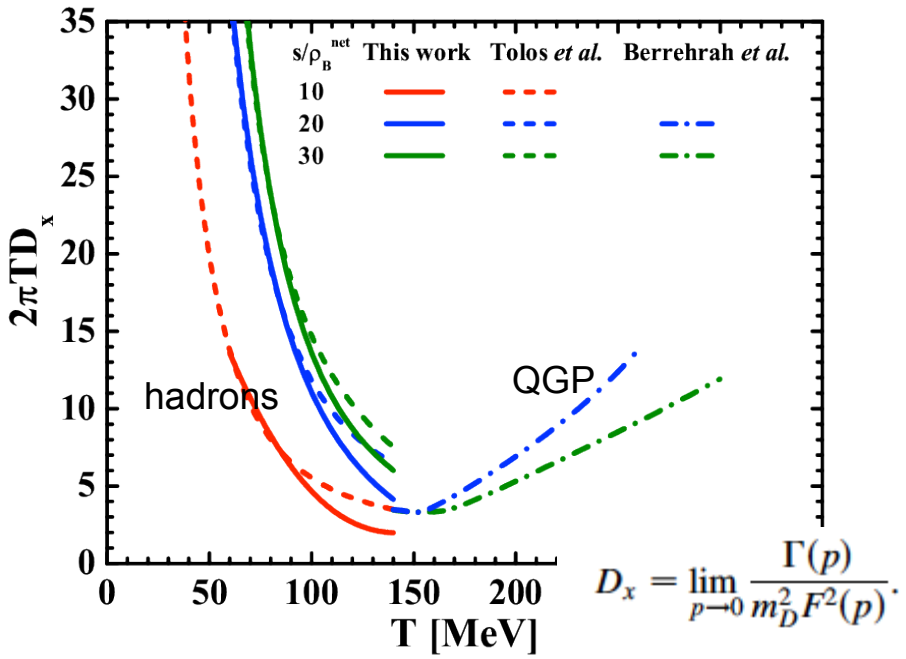


FAIR energies
5-40 AGeV





Shorter relaxation time for lower energy beams (baryons!) but do not relax ($\tau_{fireball}$~10 fm)

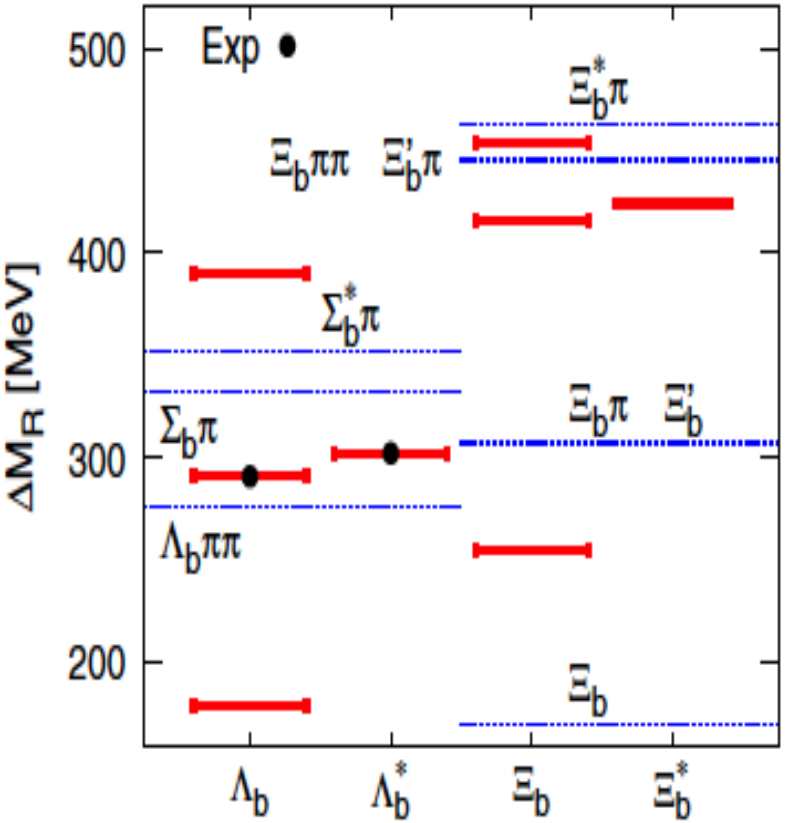


Continuous matching at T_c

Berrehrah et al. '14; Ozvenchuk et al '14

Beauty under Extreme Conditions

Spectroscopy of excited beauty baryons



Garcia-Recio, Nieves, Romanets, Salcedo and LT '13

$\Lambda_b(5912)$ and $\Lambda^*_b(5920)$ found by LHCb* collaboration are described as meson-baryon molecular states belonging to a HQSS doublet. New HQSS partners are predicted: $\Xi_b(6035)$ and $\Xi_b(6043)$

* Aaij et al (LHCb) '12

B meson propagation in dense hot matter

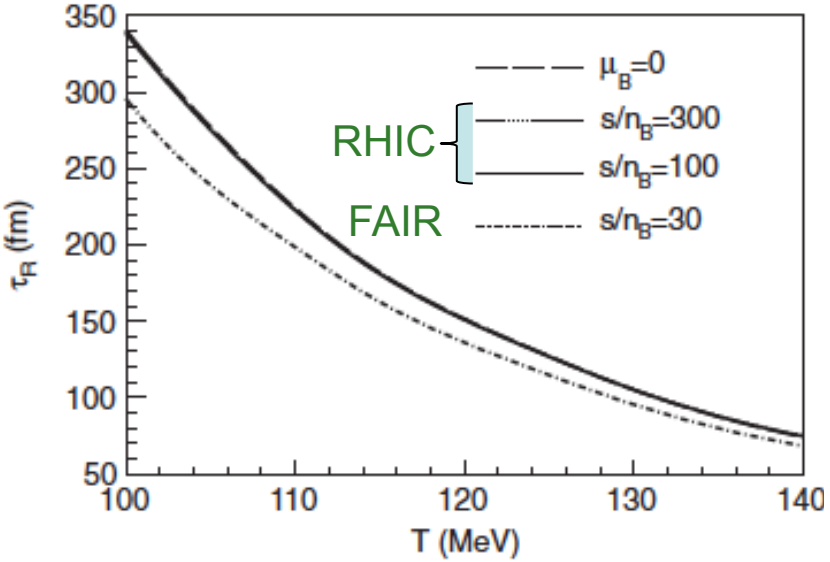
Fokker-Planck equation

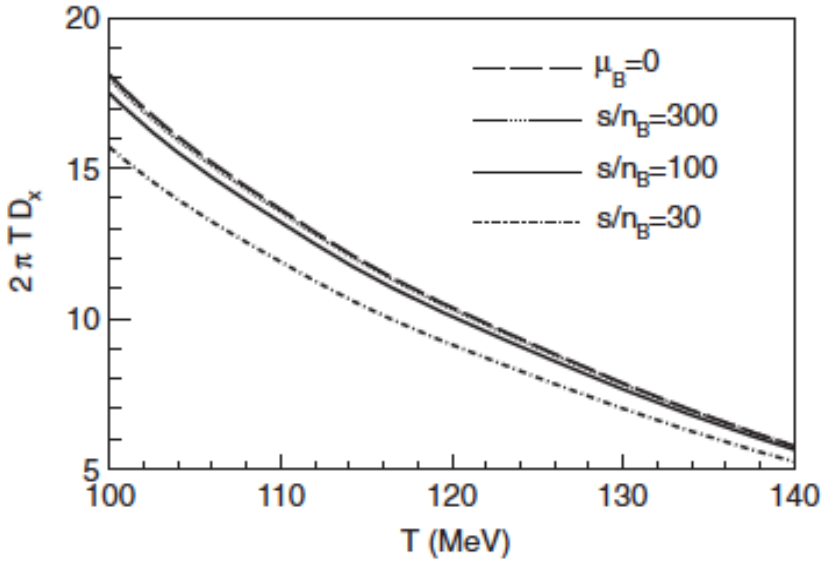
$$\frac{\partial f(t,\mathbf{p})}{\partial t} = \frac{\partial}{\partial p_i}\left\{F_i(\mathbf{p}) f(t,\mathbf{p}) + \frac{\partial}{\partial p_j}\left[\Gamma_{ij}(\mathbf{p}) f(t,\mathbf{p})\right]\right\},$$

drag force — diffusion coefficient

Results from FAIR to RHIC energies

Torres-Rincon, LT and Romanets '14





Bottom can hardly relax during expansion fireball ($\tau_{fireball}$~10 fm)
Results insensitive to trajectory for high s/n$_B$:
prediction for behaviour of hadronic medium at RHIC energies

Summary

- it is an exciting moment
- moving from the light to the heavy sector
- a lot of theoretical effort is needed
- but in close connection to experiments in laboratories

GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD
Study of Strongly Interacting Matter
HadronPhysics
01 Grant Agreement
MARIE CURIE ACTIONS