The 31st Reimei Workshop on Hadron Physics in Extreme Conditions at J-PARC
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Heavy Hadrons @ Extremes

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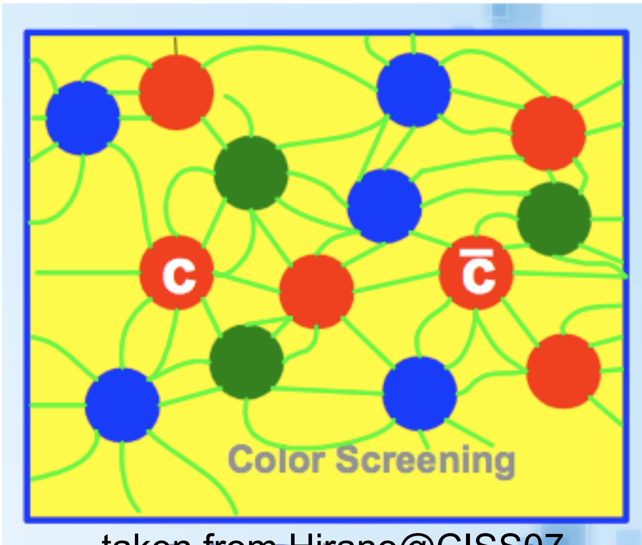
and J. Yamagata-Sekihara

Charm under Extreme Conditions

J/Ψ suppression

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



taken from Hirano@CISS07

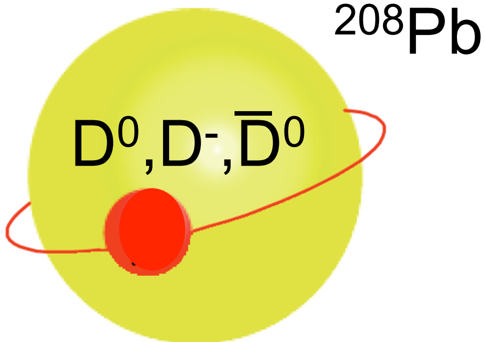
but also comover scattering

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

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

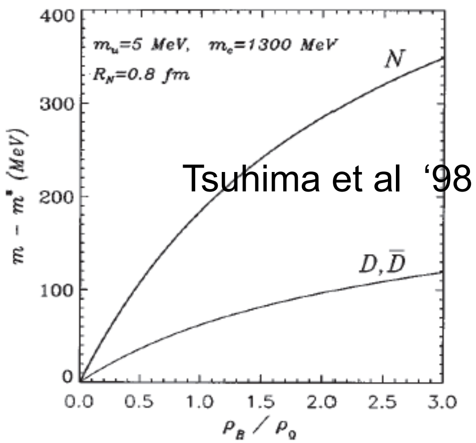
D-mesic nuclei

Tsushima et al '99,
Garcia-Recio et al '10
Garcia-Recio et al '12
Yasui et al '12,
Yamagata-Sekihara '16..



QMC model

exchange of ω, ρ, σ mesons among quarks in a meson/baryon bag

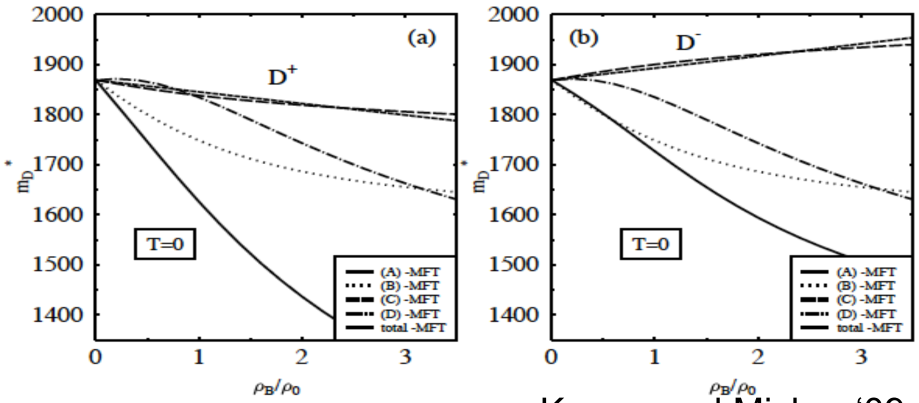


Tsuhima et al '98

Tsushima, Thomas, Sibirtsev, Fountoura..

MF/RHF model

Mazumdar, Mishra, Kumar,..

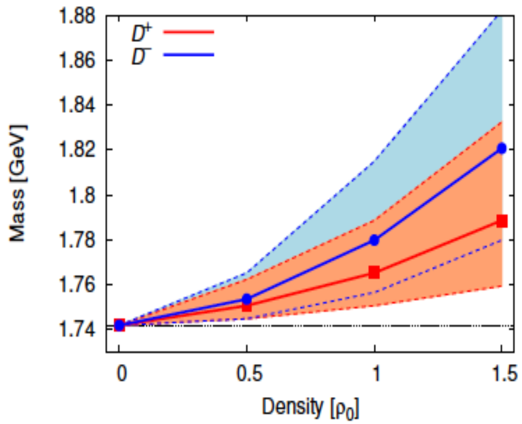


Kumra and Mishra '09

Mean-field or RHF approach to effective lagrangian generalized to include charmed mesons

QCD sum-rule

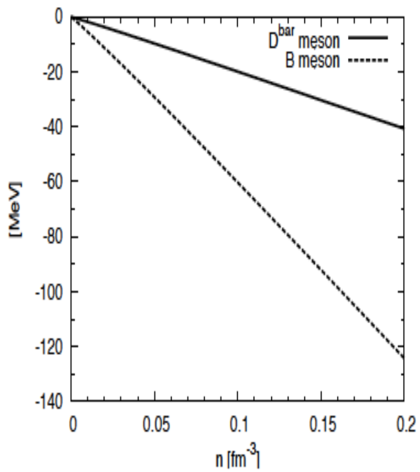
Gubler, Hayashigaki, Hilger, Kaempfer, Leupold, Nielsen, Navarra, Oka, Suzuki, Thomas, Weise, ..



Suzuki, Gubler and Oka '15

operator product expansion for in-medium correlation function and relate it to the spectral function

π exchange



heavy meson - nucleon interaction mediated by π exchange

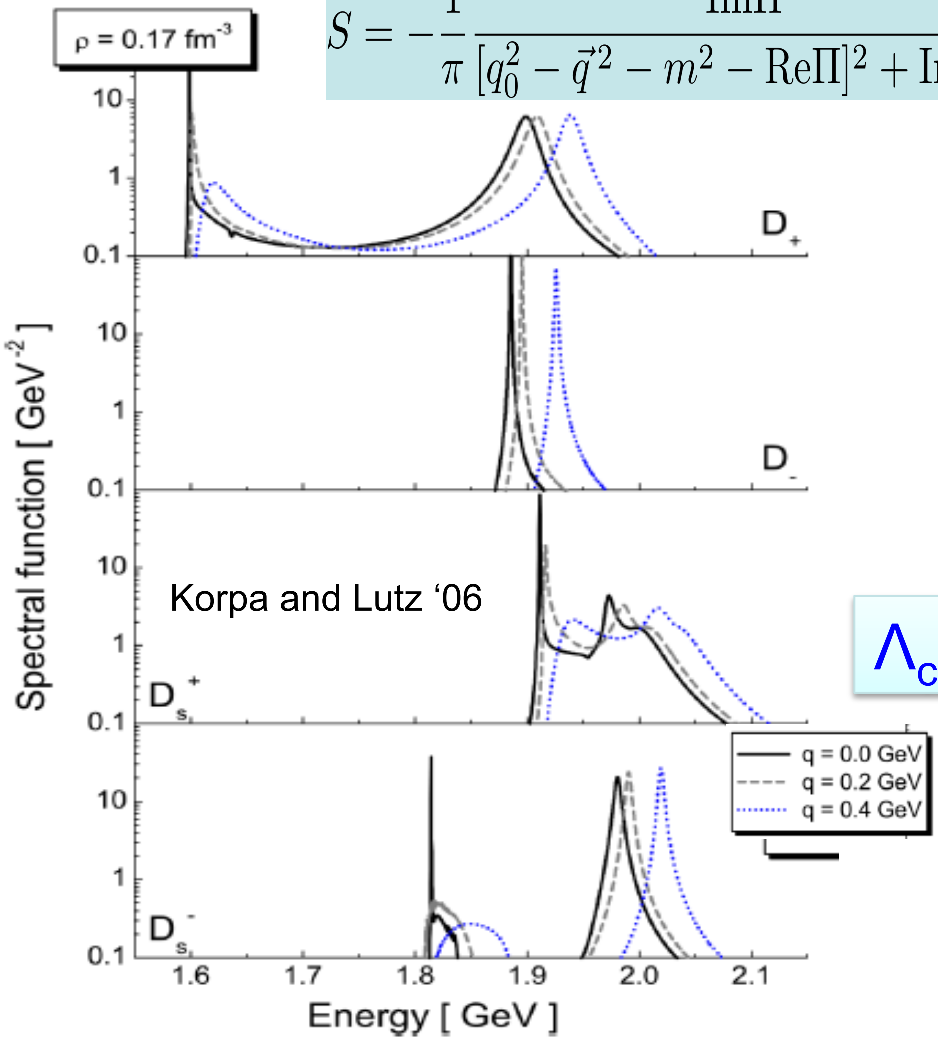
Yasui and Sudoh '13

Unitarized theory in matter

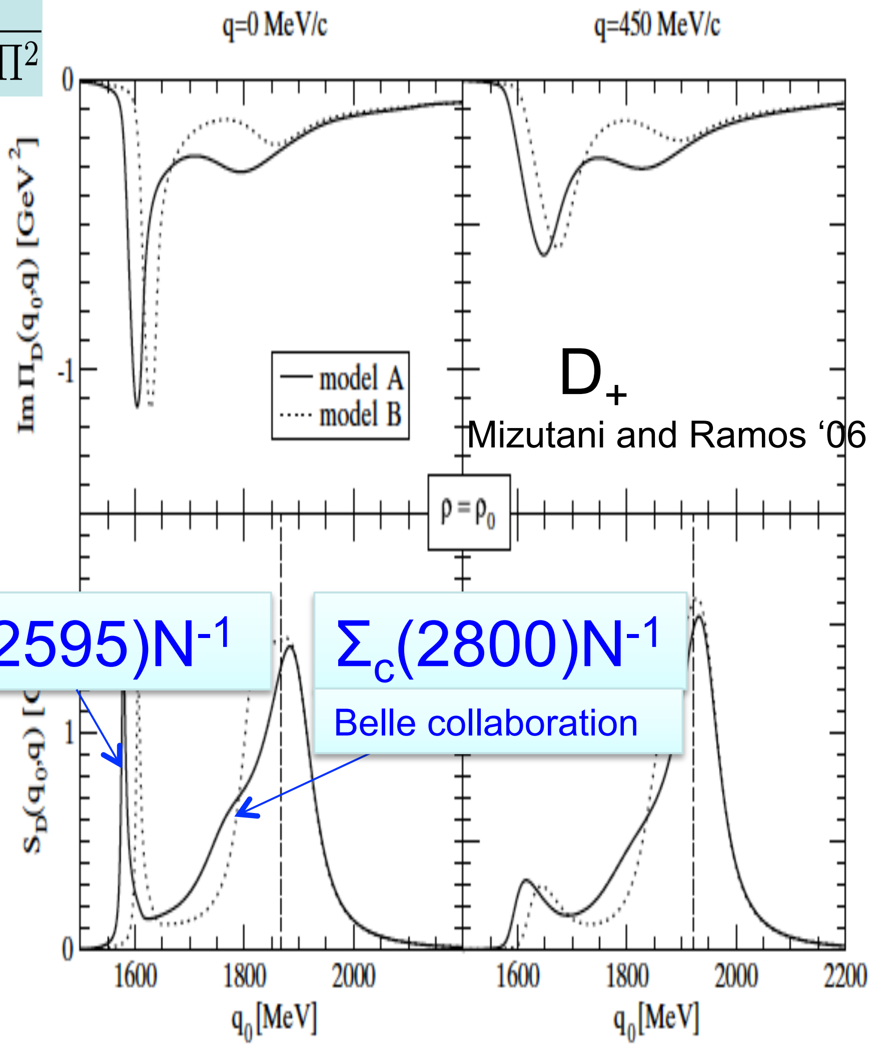
selfconsistent coupled-channel procedure

(bare interaction saturated by t-channel vector-meson exchange)

$$S = -\frac{1}{\pi}\frac{\mathrm{Im}\Pi}{[q_0^2 - \vec{q}^{\,2} - m^2 - \mathrm{Re}\Pi]^2 + \mathrm{Im}\Pi^2}$$



Lutz, Korpa, Hofmann..



Ramos, Mizutani, Jimenez-Tejero, Vidana, LT,..

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

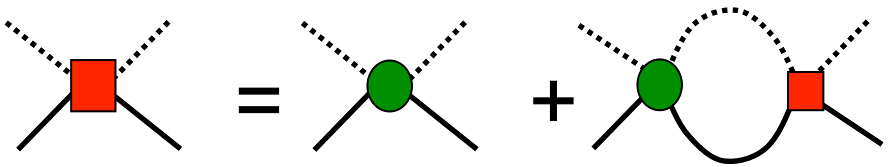
HQSS*: spin interactions vanish for infinitely massive quarks

*Isgur, Wise, Manohar, Neubert

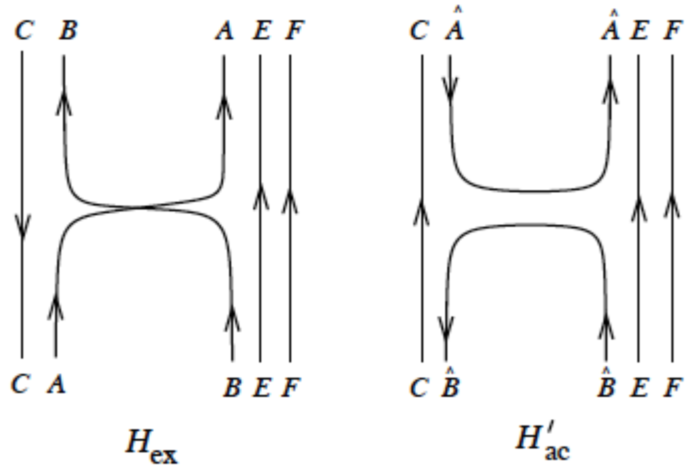
To construct a model for four flavors for pseudoscalar and vector mesons as well as $1/2^+$ and $3/2^+$ baryons that incorporates HQSS in the charm sector: extended WT interaction that fulfills SU(6)xHQSS and it is consistent with chiral symmetry in the light sector

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

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



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



H_{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

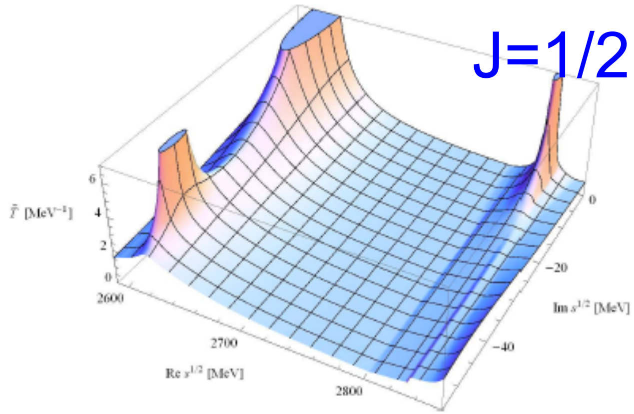
Λ_c : C=1,S=0,I=0

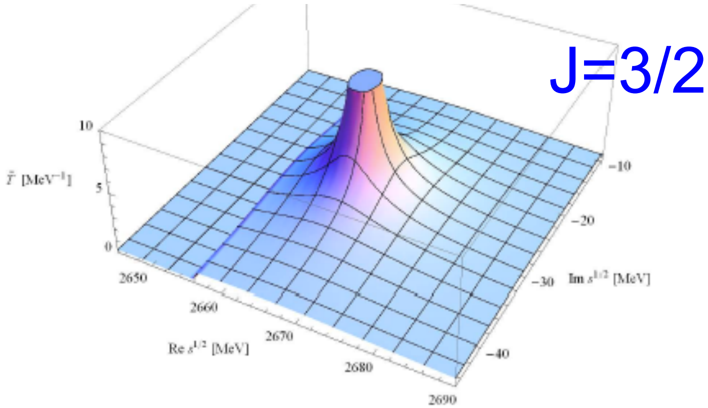
Garcia-Recio et al.’09;
Romanets et al. ’12

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

coupling constant

mass and width





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	$g_{\Sigma_c\pi} = \mathbf{0.}$[illegible], $g_{ND} = 3.5$, $g_{ND^*} = 5.6$, $g_{\Lambda D_s} = 1.4$, $g_{\Lambda D_s^*} = 2.9$, $g_{\Lambda_c\eta} = 0.9$	$\Lambda_c(2595)$ ***	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

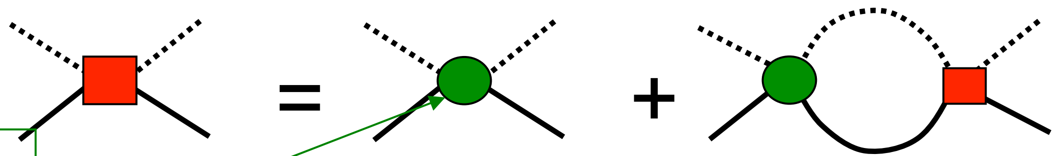
- Λ_c(2595) has large DN and D*N components
- Double-pole pattern for Λ_c(2595), like for Λ(1405)
- Identification of Λ_c(2625)

Charmed hadrons in matter

Unitarized theory in matter:

selfconsistent coupled-channel procedure

Free space

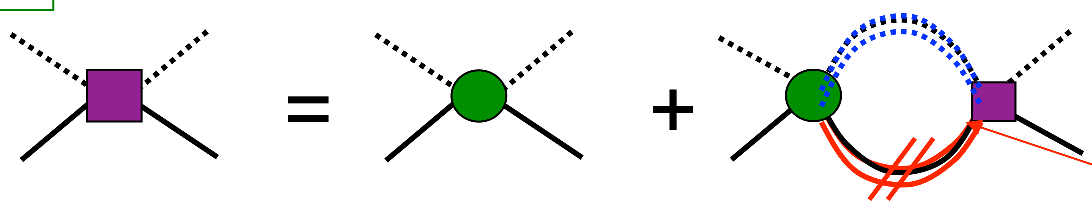


potential from extended WT interaction that respect HQSS

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

meson dressing

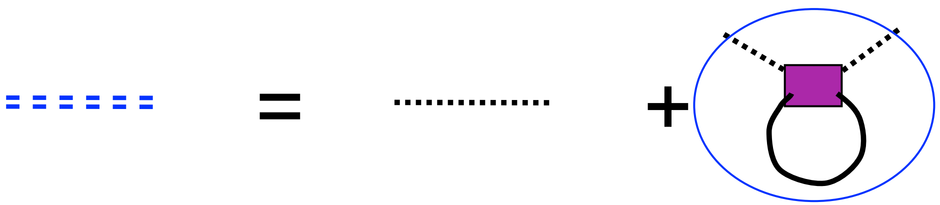
Medium



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

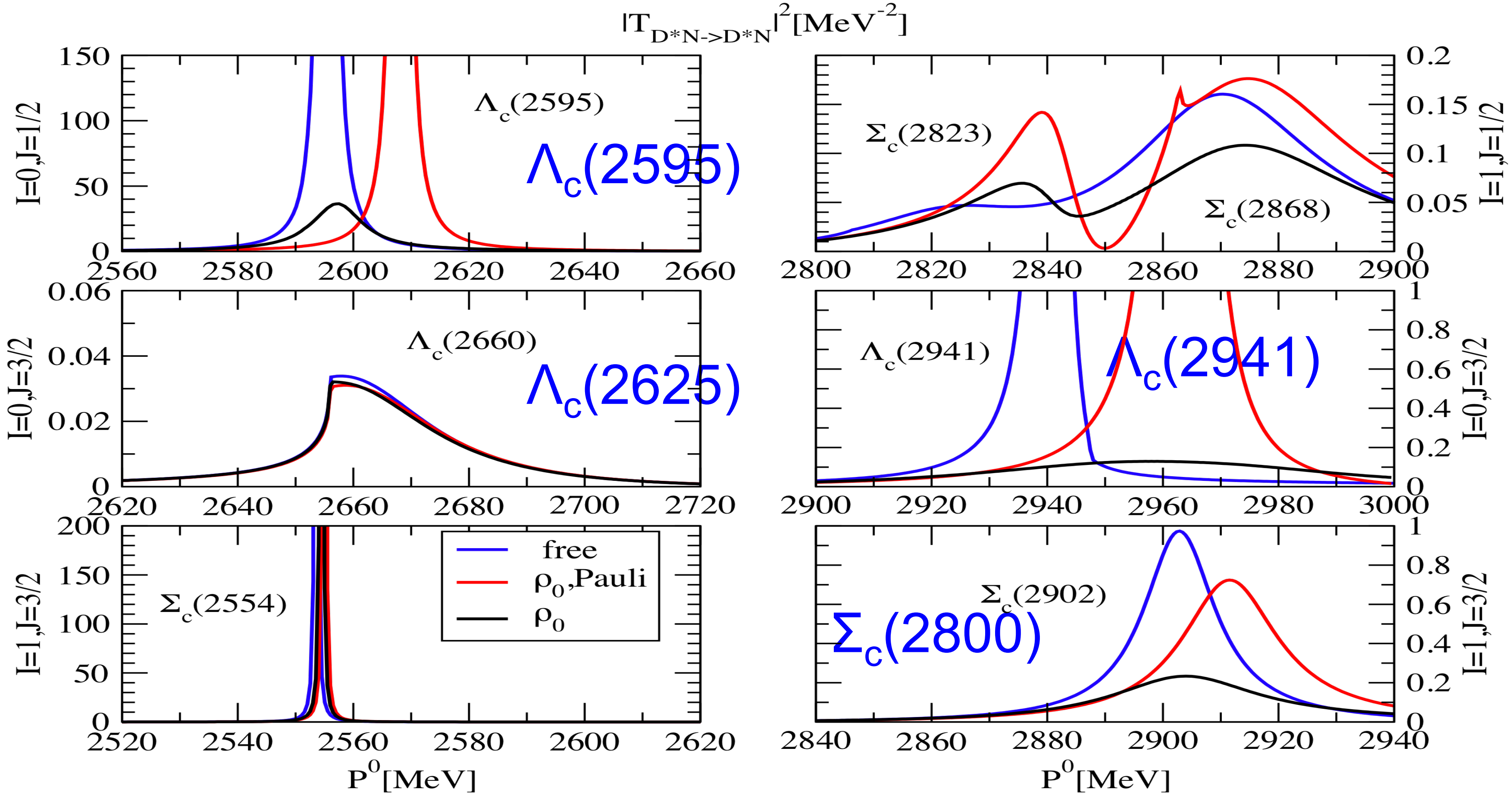
PDG

Resonance	$I(J^P)$	Status	Mass [MeV]	Γ [MeV]
$\Lambda_c(2595)$	$0(1/2^-)$	***	2592.25 ± 0.28	2.6 ± 0.6
$\Lambda_c(2625)$	$0(3/2^-)$	***	2628.11 ± 0.19	< 0.97
$\Lambda_c(2765)$	$?(?^?)$	*	2766.6 ± 2.4	50
or $\Sigma_c(2765)$				
$\Lambda_c(2880)$	$0(5/2^+)$	***	2881.53 ± 0.35	5.8 ± 1.1
$\Lambda_c(2940)$	$0(?^?)$	***	$2939.3 + 1.4 - 1.5$	$17 + 8 - 6$
$\Sigma_c(2800)^{++}$	$1(?^?)$	***	$2801 + 4 - 6$	$75 + 22 - 17$
$\Sigma_c(2800)^{+}$	$1(?^?)$	***	$2792 + 14 - 5$	$62 + 60 - 40$
$\Sigma_c(2800)^{0}$	$1(?^?)$	***	$2806 + 5 - 7$	$72 + 22 - 15$

Dynamically-generated baryonic resonances in nuclear matter

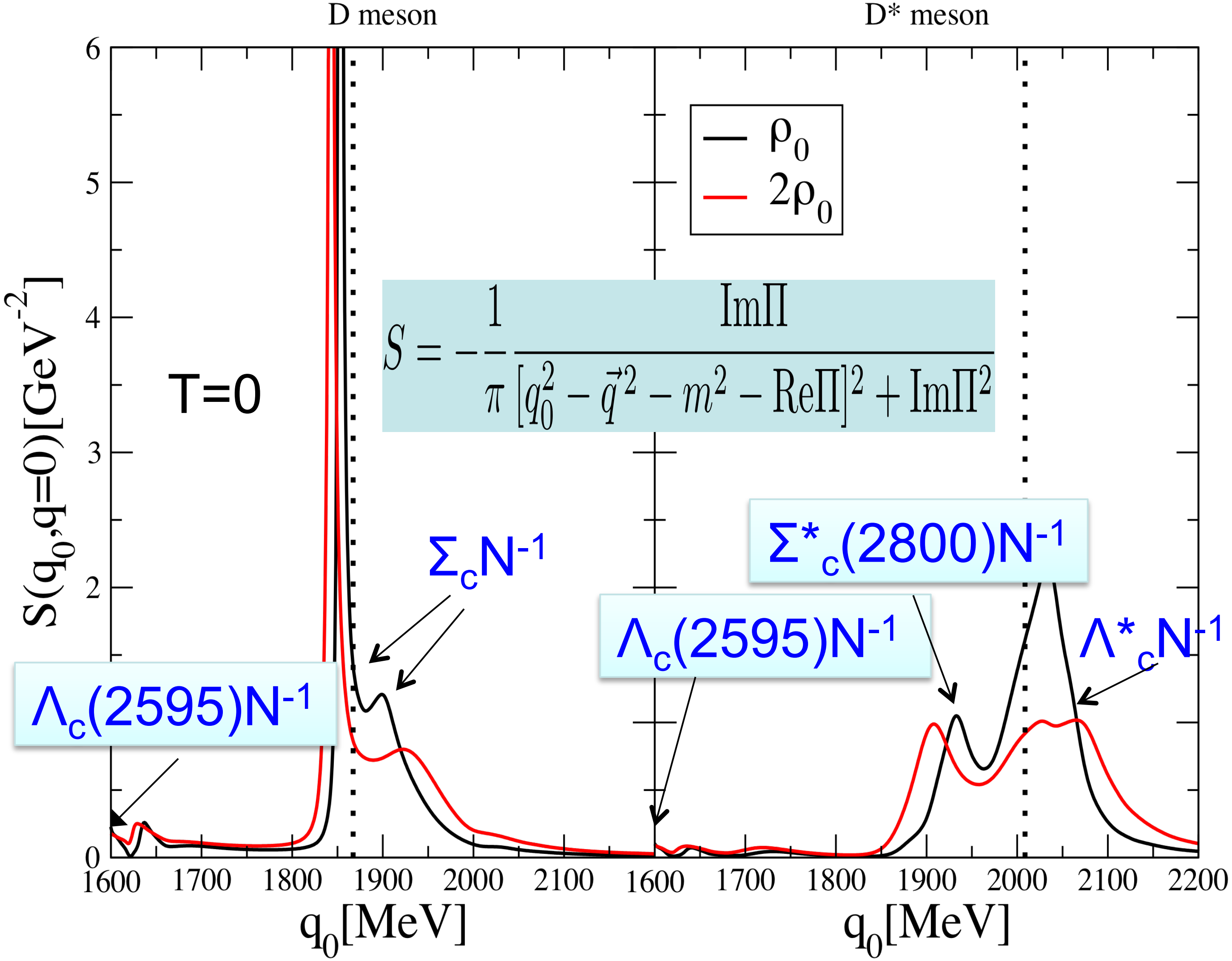
LT, Garcia-Recio and Nieves '10

[α fitted to reproduce $\Lambda_c(2595)$ and analyze energies up to 3.5 GeV]



Unitarized theory in matter:

selfconsistent coupled-channel procedure



$$S = -\frac{1}{\pi}\frac{\mathrm{Im}\Pi}{[q_0^2 - \vec{q}^{\,2} - m^2 - \mathrm{Re}\Pi]^2 + \mathrm{Im}\Pi^2}$$

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.(1) '13
Garcia-Recio et al.(2) '13

D mesic nuclei

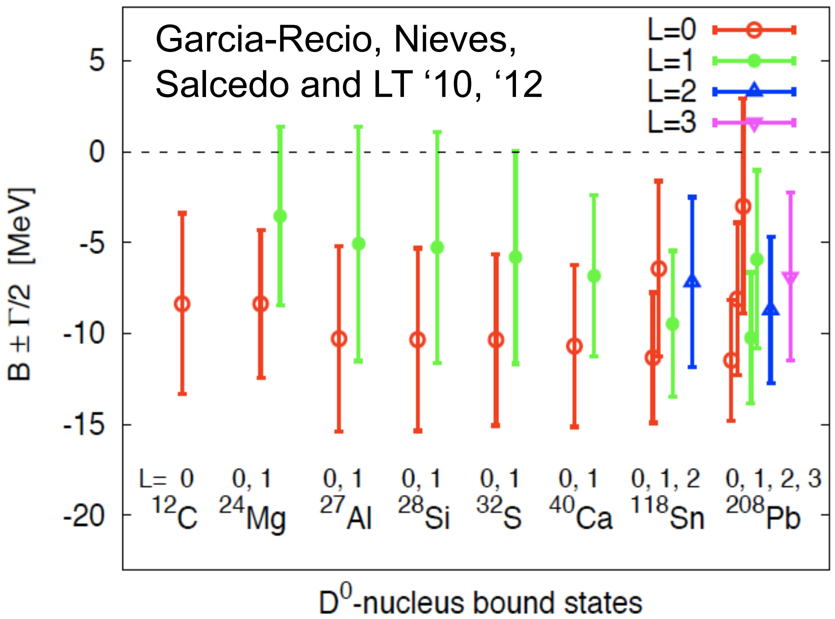
Initially predicted in ^{208}Pb within QMC model Tsushima et al. ‘99

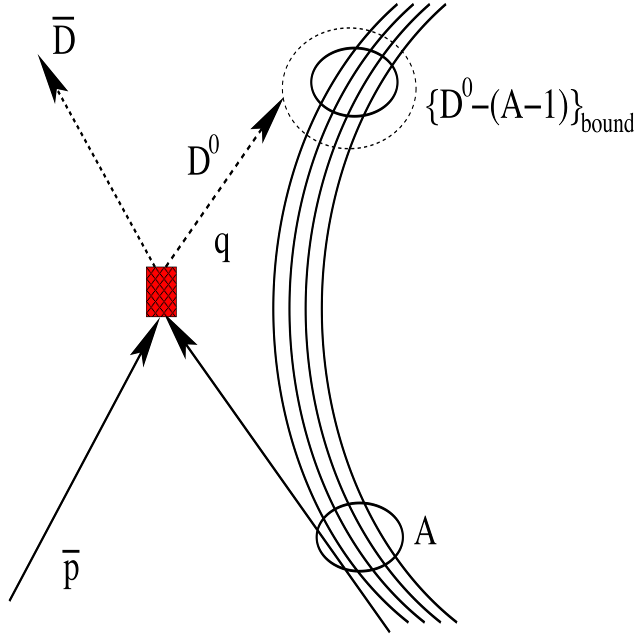
Within the self-consistent coupled-channel approach that incorporates HQSS

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

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

$$E = q^0 - m_D$$





- Weakly bound D^0-nucleus states with important widths in contrast to QMC model, while D^+ does not bind
- D^- and $\bar{D}^0$ bind in nuclei

Formation spectra of charmed meson-nucleus using an antiproton beam

@ J-PARC, PANDA (FAIR)

Yamagata-Sekira, Garcia-Recio, Nieves, Salcedo and LT '16

$$\bar{p} + {}^{12}\mathrm{C} \rightarrow \left[{}^{11}\mathrm{B} - D^{-}\right] + D^{+}$$

$$\bar{p} + {}^{12}\mathrm{C} \rightarrow \left[{}^{11}\mathrm{B} - D^{0}\right] + \bar{D}^{0}$$

Large momentum transfer (about 1 GeV/c) makes any structure due to bound states not noticeable. Need of reactions with lower momentum transfer, such as

$$\bar{p} + p \rightarrow D^{*-} + D^{+},$$

$$D^{*-} + A_Z \rightarrow \pi^0 + [A_Z - D^{-}]_b$$

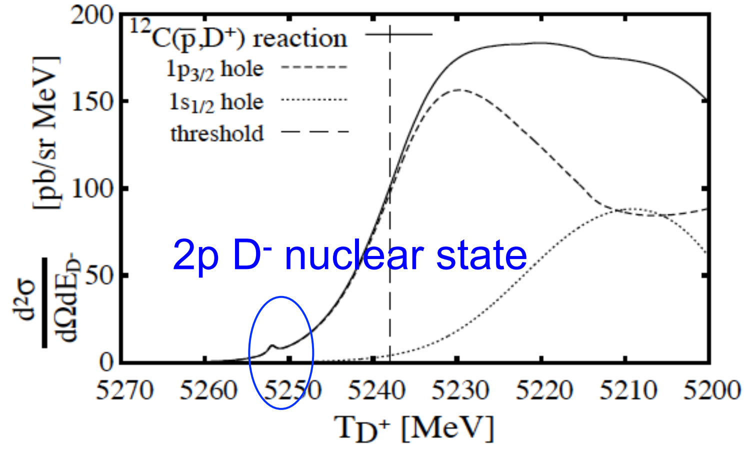


Figure 2: Formation spectrum for the $\bar{p} + {}^{12}\mathrm{C} \rightarrow \left[{}^{11}\mathrm{B} - \mathrm{D}^{-}\right] + \mathrm{D}^{+}$ reaction at $P_{\bar{p}} = 8\mathrm{GeV/c}$ and $\theta^{\mathrm{LAB}}_{D^+} = 0°$, as a function of the outgoing D^+ meson total energy. The partial contributions of some shell configurations of the final nucleus are also shown in the figure. The vertical dashed line indicates the D^- meson production threshold.

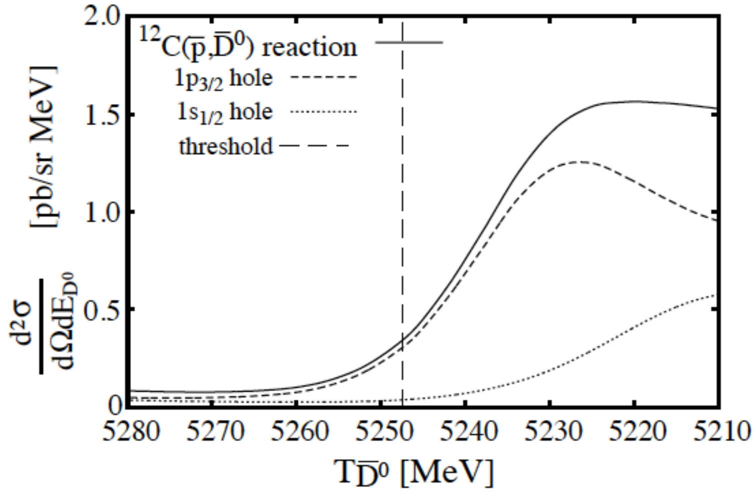


Figure 3: Same as in Fig. 2, but for the $\bar{p} + {}^{12}\mathrm{C} \rightarrow \left[{}^{11}\mathrm{B} - \mathrm{D}^{0}\right] + \bar{\mathrm{D}}^{0}$ reaction. The vertical dashed line indicates now the D^0 meson production threshold.

D meson propagation in dense hot matter

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

Fokker-Planck equation

drag force　　　　diffusion coefficient

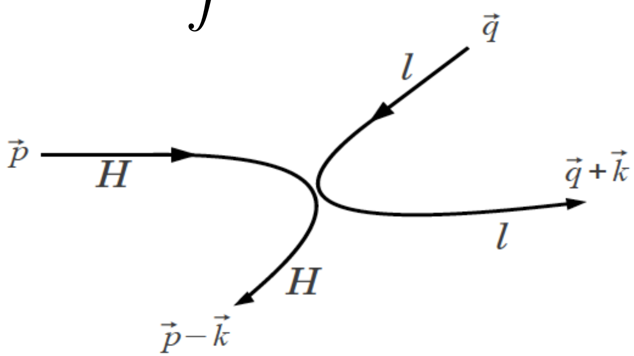
$$\frac{\partial f(t,\mathbf{p})}{\partial t} = \frac{\partial}{\partial p_i}\left\{F_i(\mathbf{p}) f(t,\mathbf{p}) + \frac{\partial}{\partial p_j}[\Gamma_{ij}(\mathbf{p}) f(t,\mathbf{p})]\right\},$$

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

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

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

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



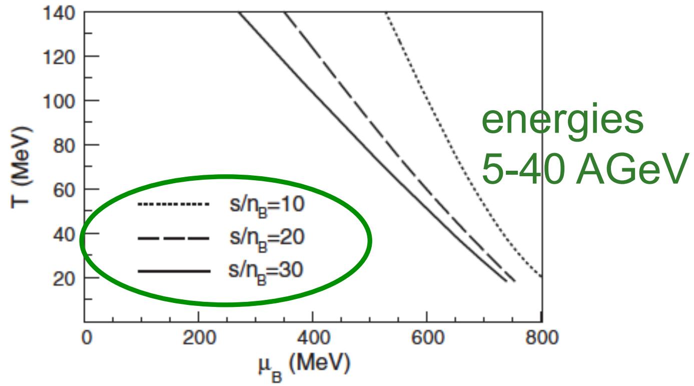
Previous works　Laine ‘11; He, Fries, Rapp ‘11; Ghosh, Das, Sarkar, -eAlam ’11

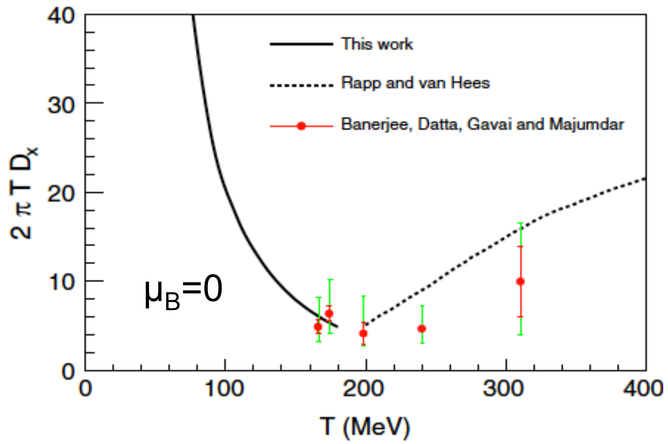
We need scattering amplitudes $|T|^2$

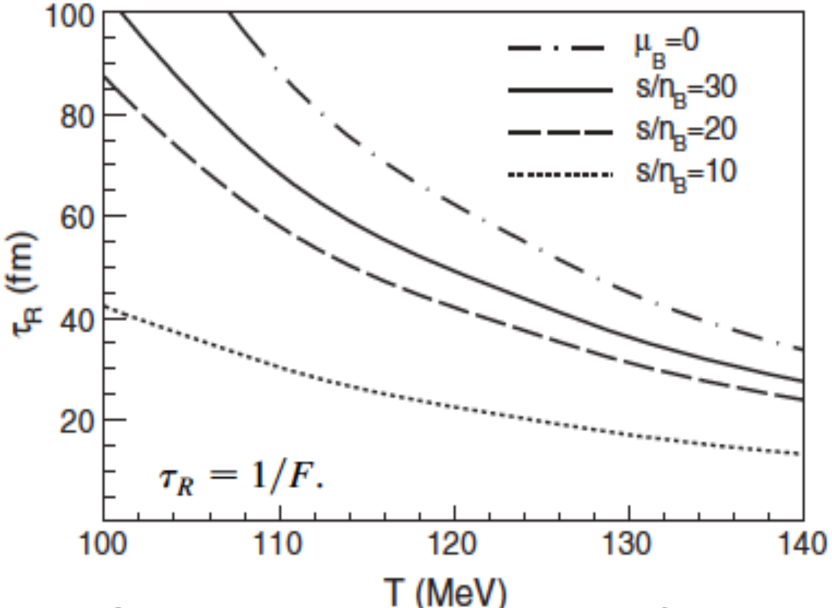
Abreu, Cabrera, Llanes-Estrada, Torres-Rincon ’11; LT and Torres-Rincon ’13

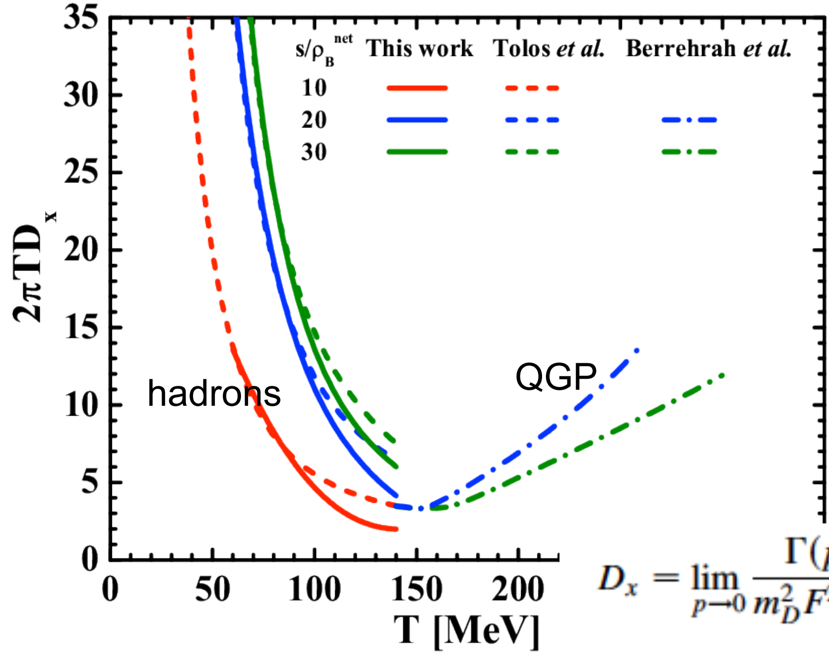
Some results for FAIR energies

LT and Torres-Rincon '13









$$D_x = \lim_{p \to 0} \frac{\Gamma(p)}{m_D^2 F^2(p)}.$$

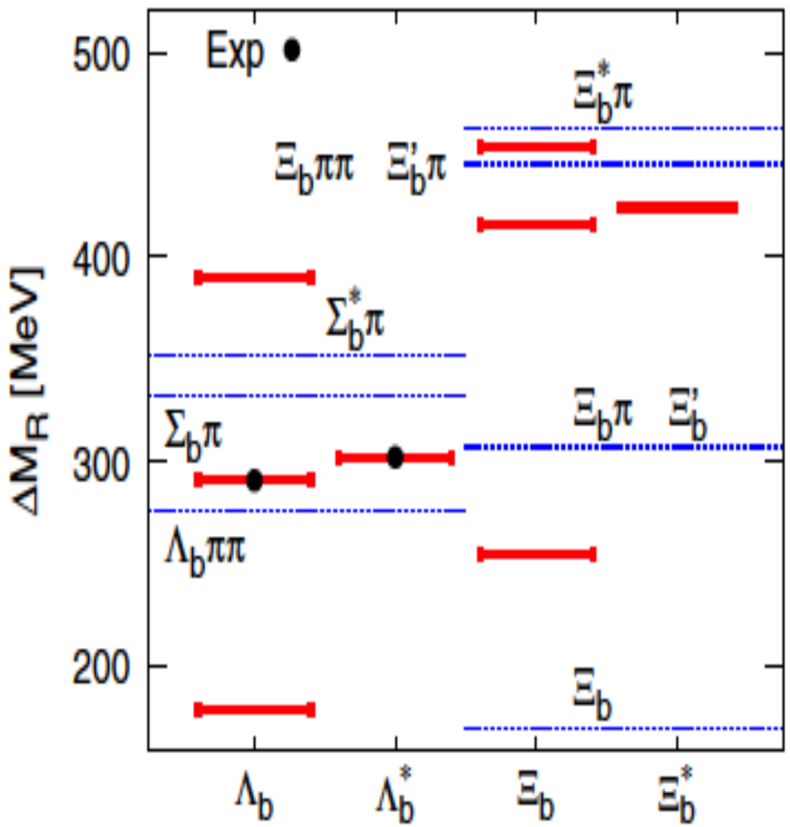
Shorter relaxation time for lower energy beams (baryons!) but do not relax ($\tau_{fireball}$~10 fm)

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

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

* Aaij et al (LHCb) '12

$\bar{B}$ meson propagation in dense hot matter

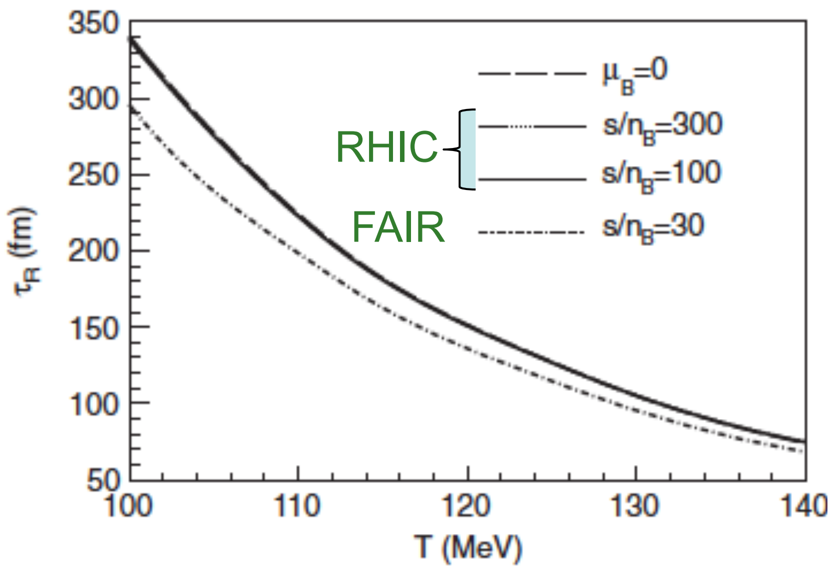
Fokker-Planck equation

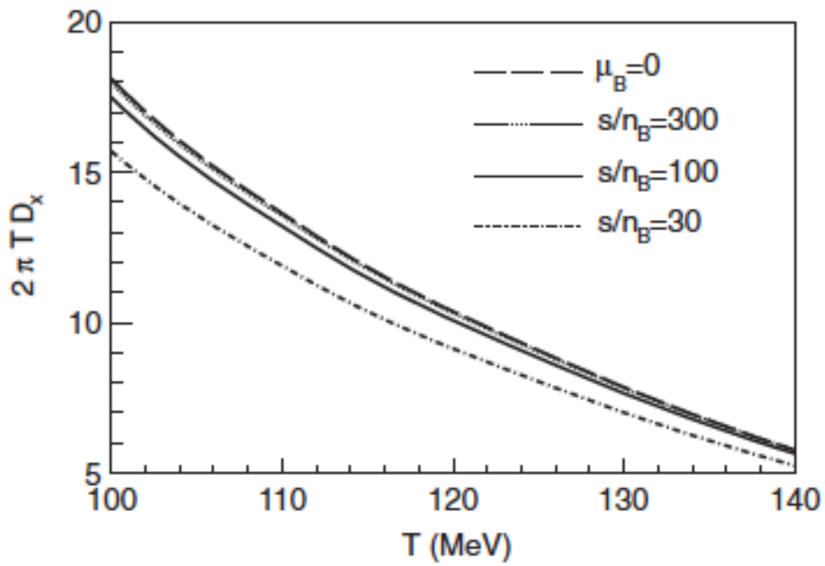
$$\frac{\partial f(t,\mathbf{p})}{\partial t} = \frac{\partial}{\partial p_i}\left\{F_i(\mathbf{p}) f(t,\mathbf{p}) + \frac{\partial}{\partial p_j}\left[\Gamma_{ij}(\mathbf{p}) f(t,\mathbf{p})\right]\right\},$$

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 charm/beauty 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 HadronPhysics3 Grant Agreement

MARIE CURIE ACTIONS