The charming beauty of the strong interaction

Institute of Space Sciences
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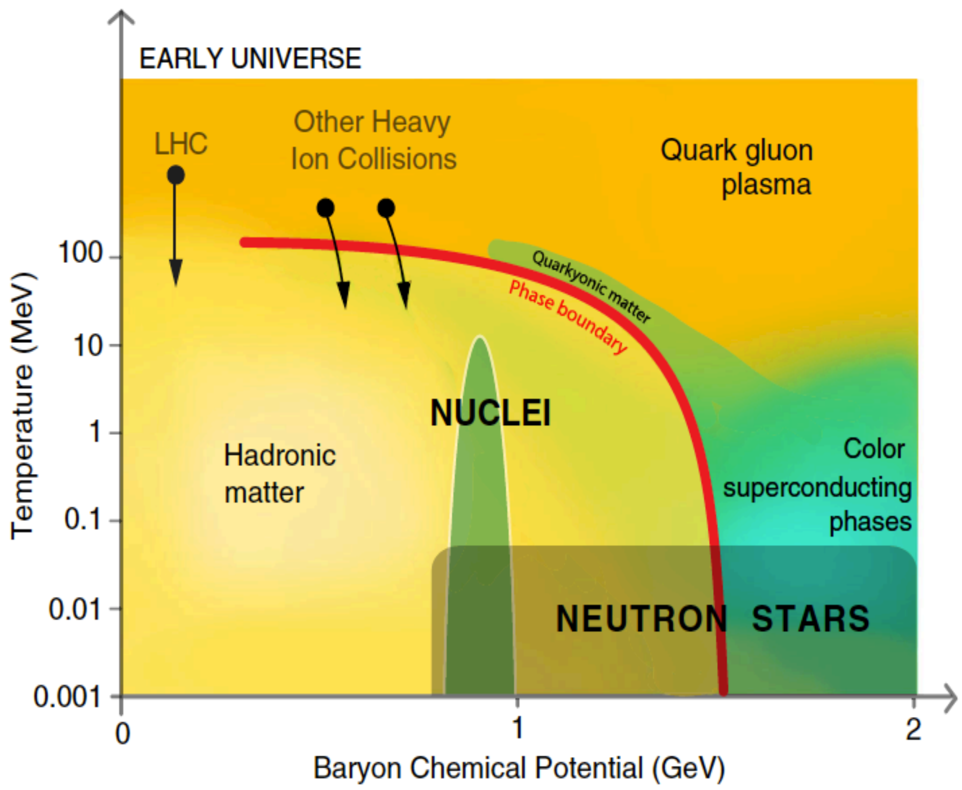
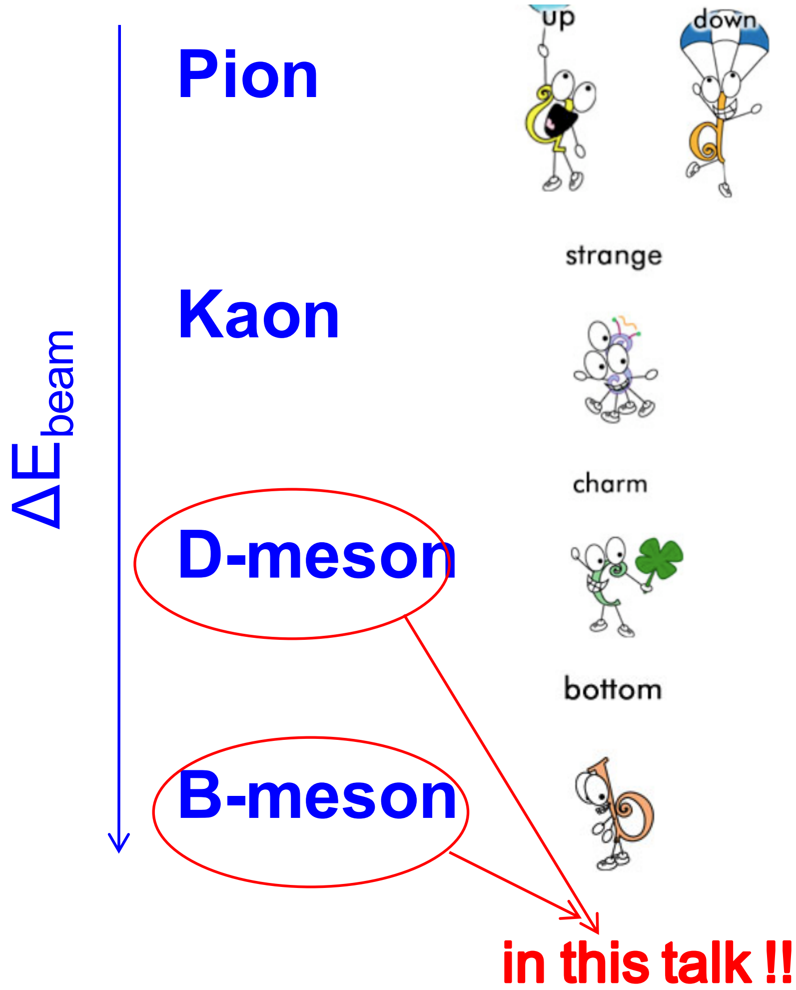
Hadrons under extreme conditions
COST THOR Working Group I Meeting
Swansea, September 12-14, 2017

What happens to hadrons at nonzero temperature and density?



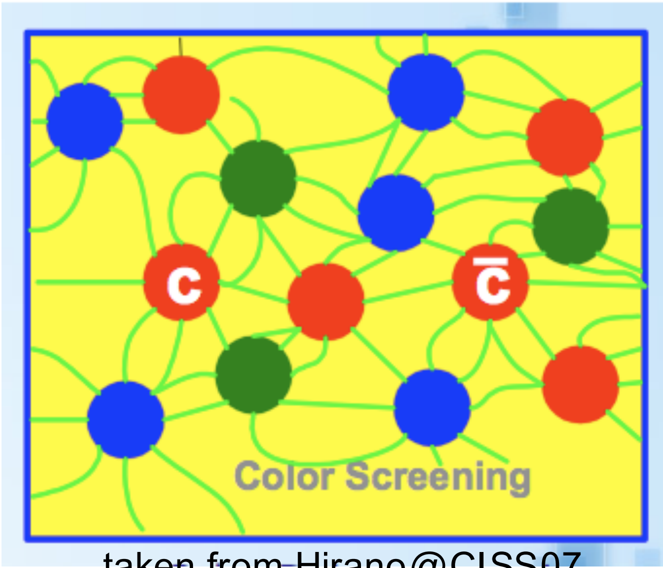
Watts et al.(LT), Rev. Mod. Phys. 88 (2016) 021001



Charm under Extreme Conditions

J/Ψ suppression

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



taken from Hirano@CISS07

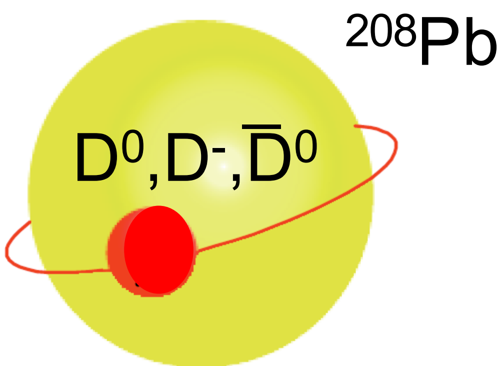
but also comover scattering

$$J/\Psi + \pi <-> D + \bar{D}$$

Capella, Armesto, 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..



Charm @ FAIR

- Open Charm spectroscopy:

- Charmonium above open charm:
Ψ, X_{cJ}, h_c,…Interesting case: X(3872)
- Charmed exotics (multiquark states)
- Charmed hybrids

- Charm in nuclei (?):

- J/Ψ +N cross sections
- Ψ(3770),Ψ',X_{c2} decay in open charm

- CPV with charm mesons

FAIR-ESAC/Pbar/Technical Progress Report

Open Charm Probes of
Hot and Dense Matter

- Charm-Quark Interactions in QGP

- Charm-Nucleon and Charm-Nucleus Interaction in Hot Dense Hadronic Matter

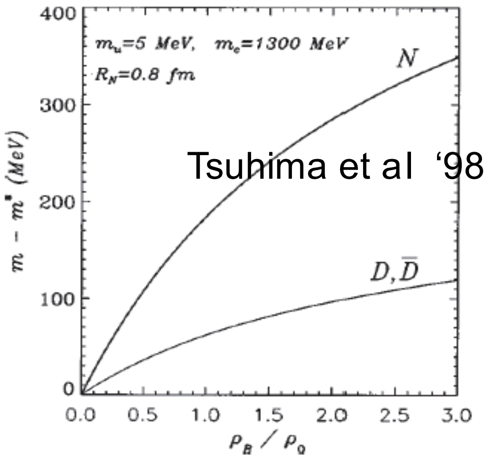
- Charmed Baryonic Resonances in Heavy-ion Collisions

The CBM Physics Book
Lecture Notes in Physics
Vol. 814 (2010) 1-980

Theoretical models in matter

QMC model

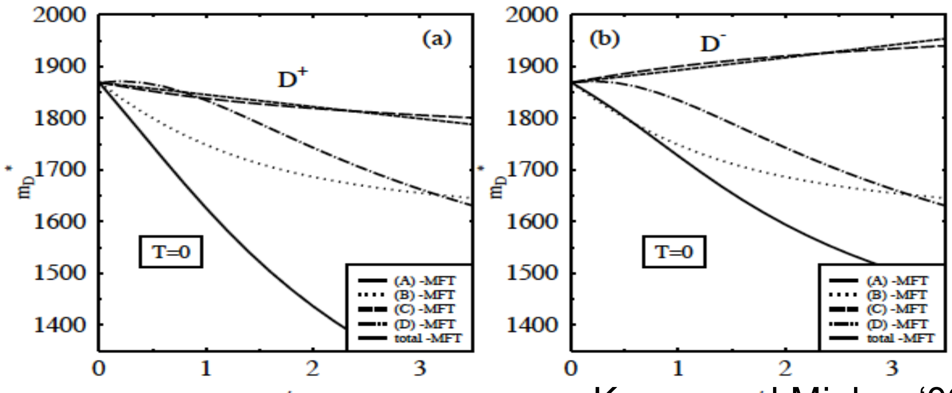
exchange of ω, ρ, σ mesons among quarks in hadron bag



Tsushima, Thomas, Sibirtsev, Fountoura..

MF/RHF model

Mazumdar, Mishra, Kumar,..

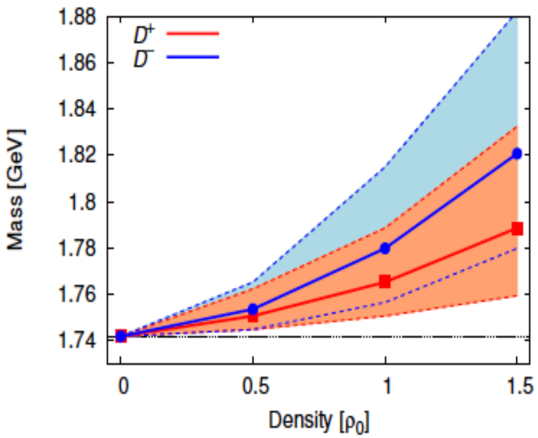


Kumra and Mishra ‘09

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

QCD sum-rule

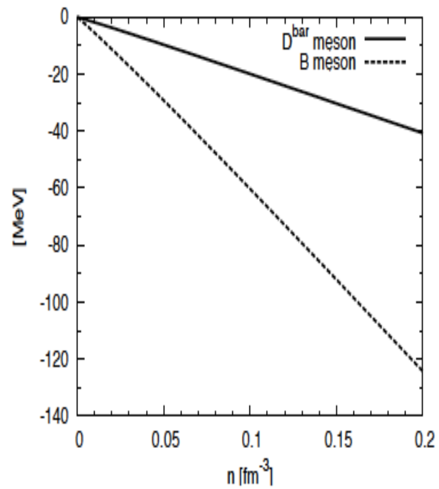
Gubler, Hayashigaki, Hilger, Kaempfer, Leupold, Nielsen, Navarra, Oka, Suzuki, Thomas, Weise, ..



Suzuki, Gubler and Oka ‘15

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

π exchange

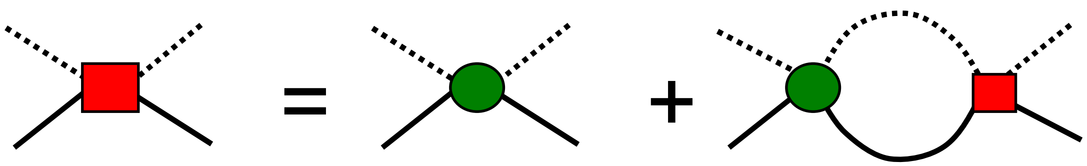


heavy meson - nucleon interaction mediated by π exchange

Yasui and Sudoh ‘13

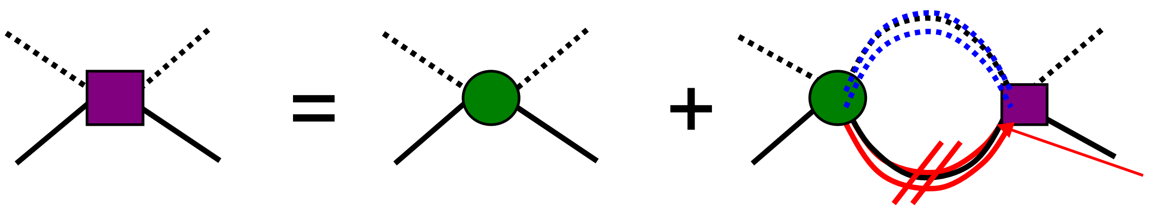
Unitarized theory in matter:
selfconsistent coupled-channel procedure

Free space



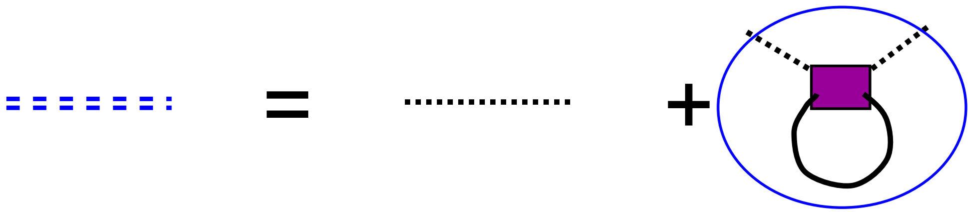
$$T_{ij} = V_{ij} + V_{il}\, G_l\, T_{lj}$$

Medium



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

Dressed meson:



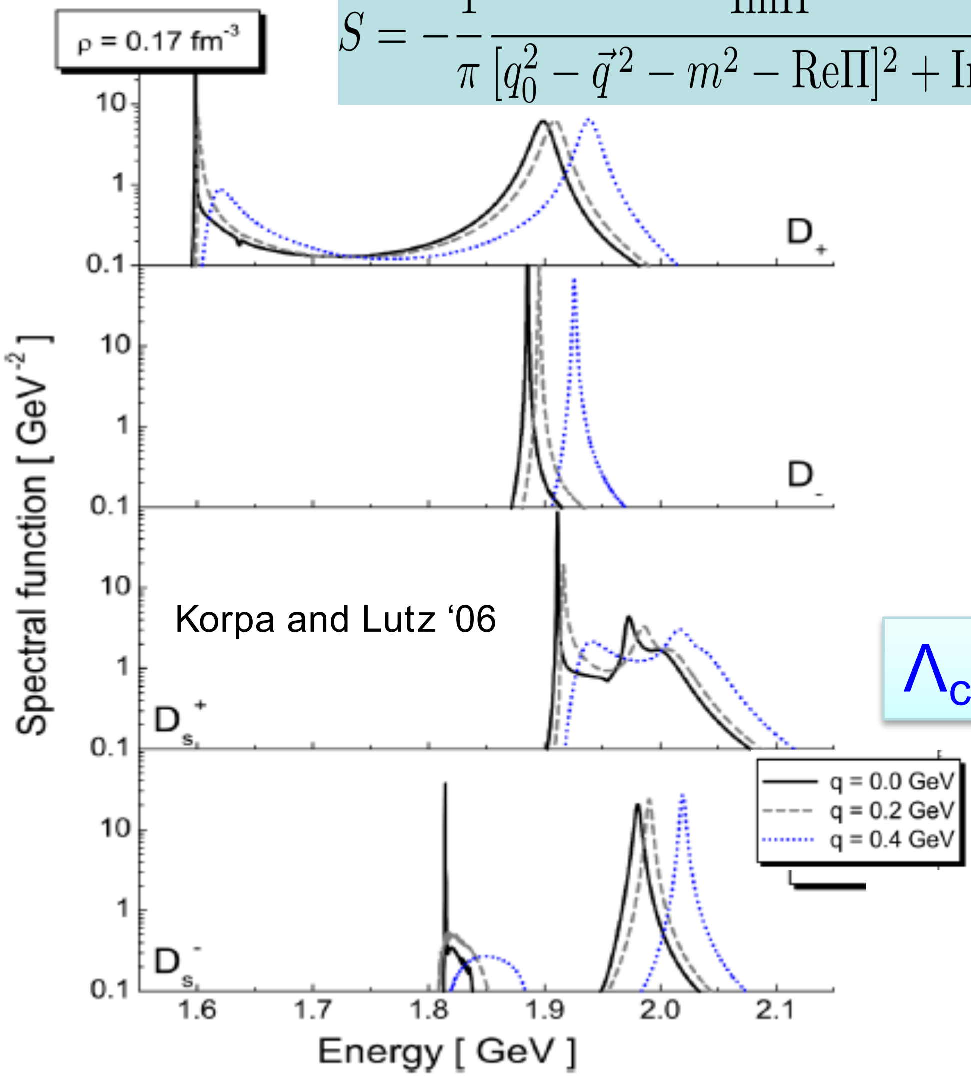
Π self-energy

Unitarized theory in matter

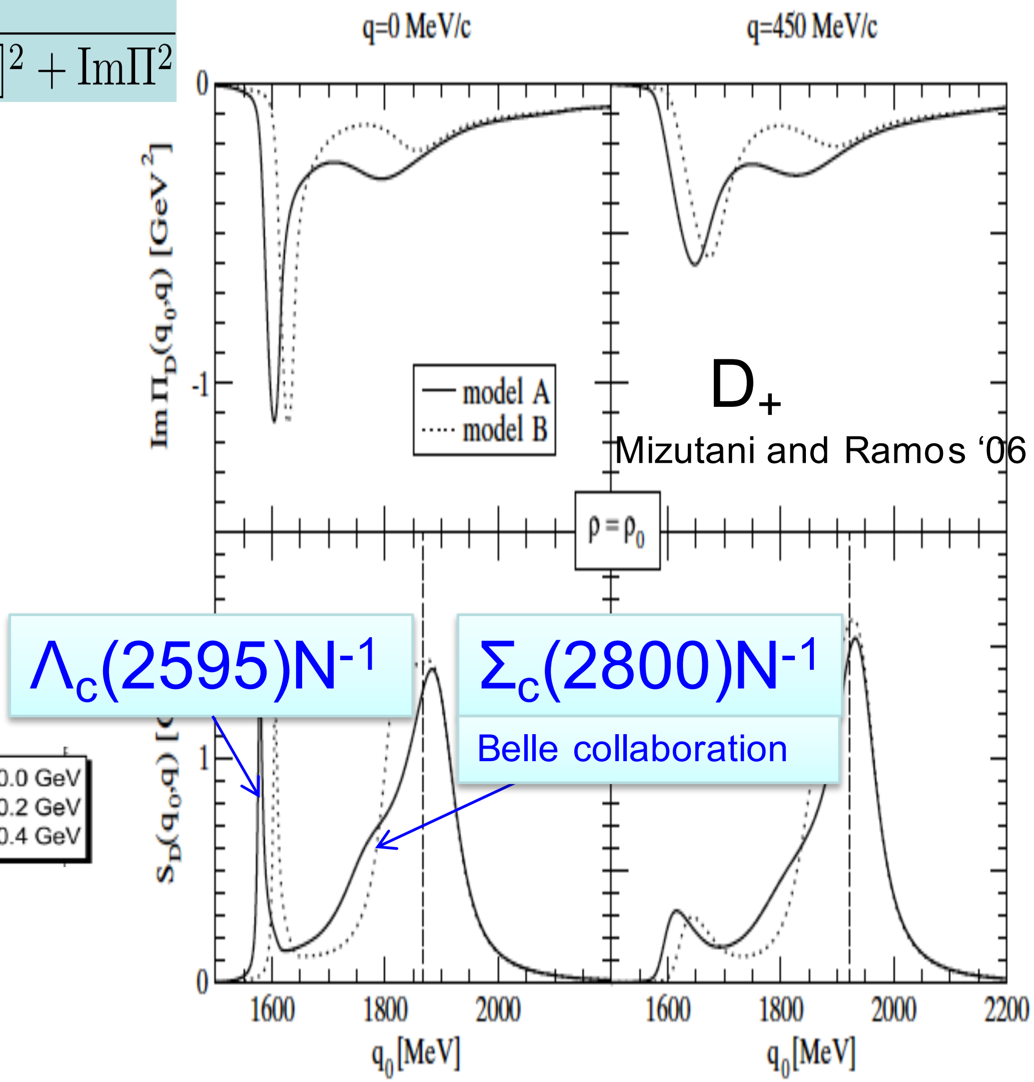
selfconsistent coupled-channel procedure

(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

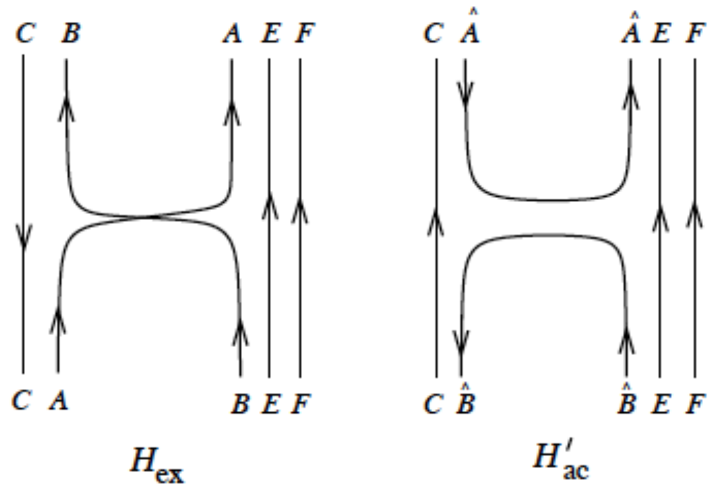
*Isgur, Wise, Manohar, Neubert

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

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

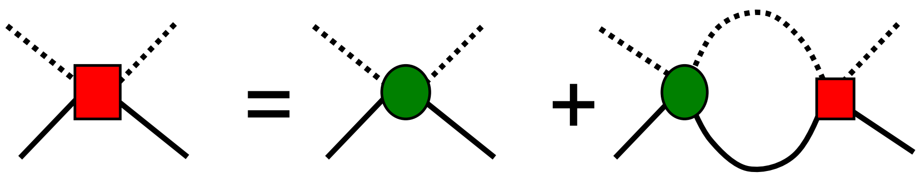
K(s): depends on meson-baryon energy

f: decay constant



H_{ex}: exchange of quarks

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



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

Spectroscopy of excited charmed baryons

Λ_c : C=1,S=0,I=0

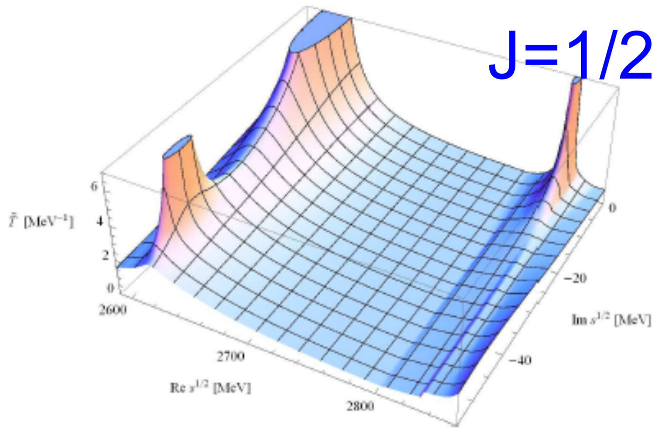
Garcia-Recio et al.'09;
Romanets et al. '12

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

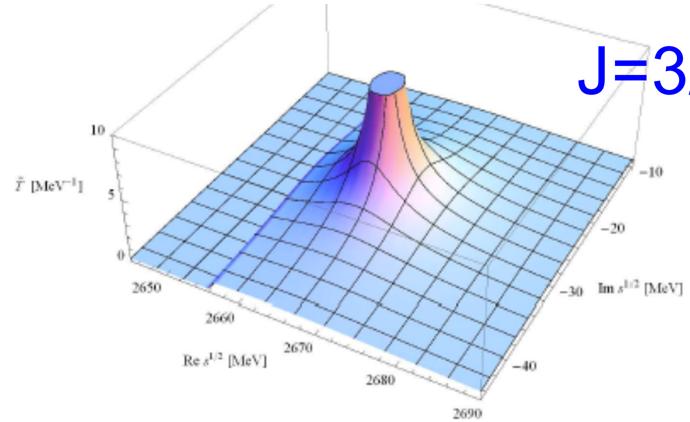
coupling constant

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	$g_{\Sigma_c\pi} = \mathbf{0.3}$, $g_{ND} = 3.5$, $g_{ND^*} = 5.6$, $g_{\Lambda D_s} = 1.4$, $g_{\Lambda D_s^*} = 2.9$, $g_{\Lambda_c\eta} = 0.9$	$\Lambda_c(2595)$ ***	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

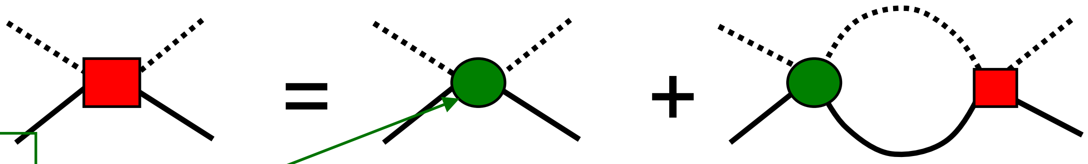
- $\Lambda_c(2595)$ has large DN and D*N components
- Double-pole pattern for $\Lambda_c(2595)$, like for $\Lambda(1405)$
- Identification of $\Lambda_c(2625)$

Charmed hadrons in matter

Unitarized theory in matter:

selfconsistent coupled-channel procedure

Free space

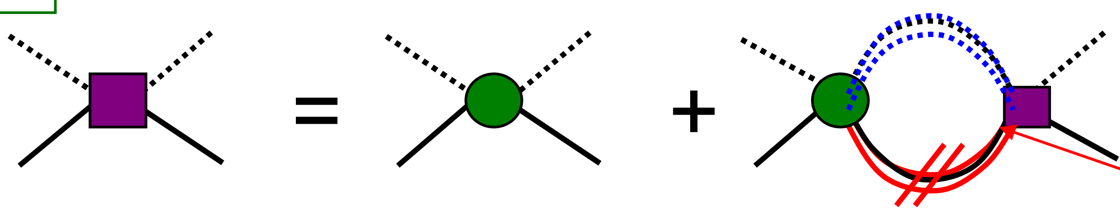


potential from extended WT interaction that respect HQSS

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

meson dressing

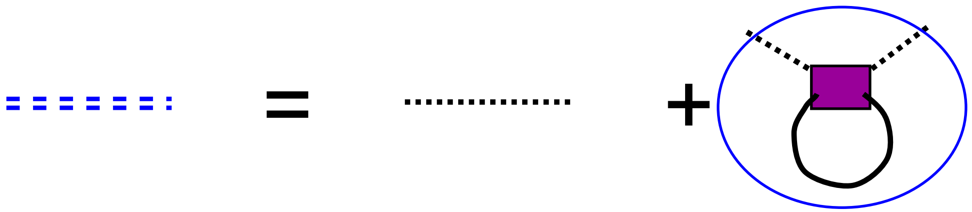
Medium



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

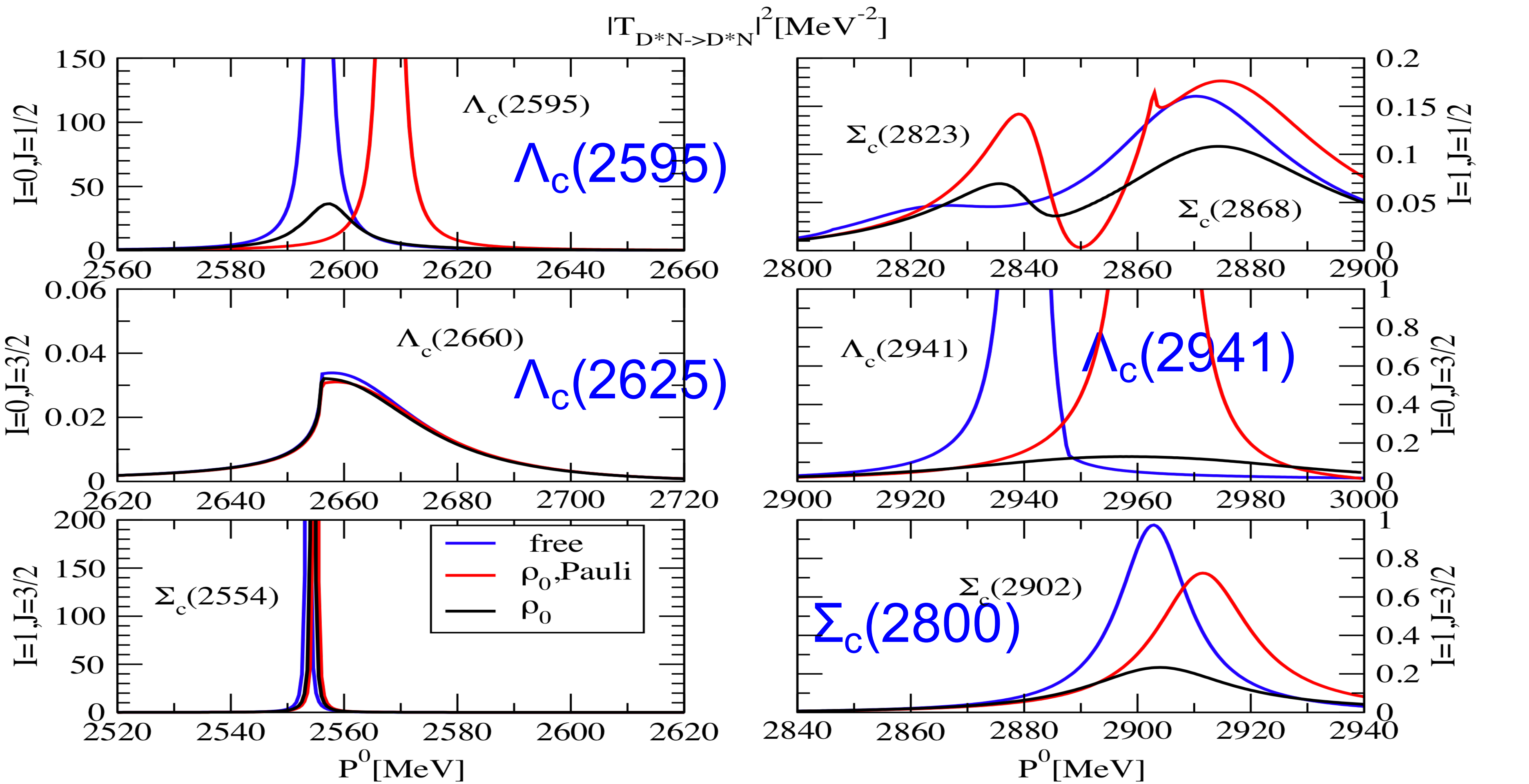
PDG

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
$\Lambda_c(2765)$ or $\Sigma_c(2765)$	$?(?^?)$	*	2766.6 ± 2.4	50
$\Lambda_c(2880)$	$0(5/2^+)$	***	2881.53 ± 0.35	5.8 ± 1.1
$\Lambda_c(2940)$	$0(?^?)$	***	$2939.3 + 1.4 - 1.5$	$17 + 8 - 6$
$\Sigma_c(2800)^{++}$	$1(?^?)$	***	$2801 + 4 - 6$	$75 + 22 - 17$
$\Sigma_c(2800)^{+}$	$1(?^?)$	***	$2792 + 14 - 5$	$62 + 60 - 40$
$\Sigma_c(2800)^{0}$	$1(?^?)$	***	$2806 + 5 - 7$	$72 + 22 - 15$

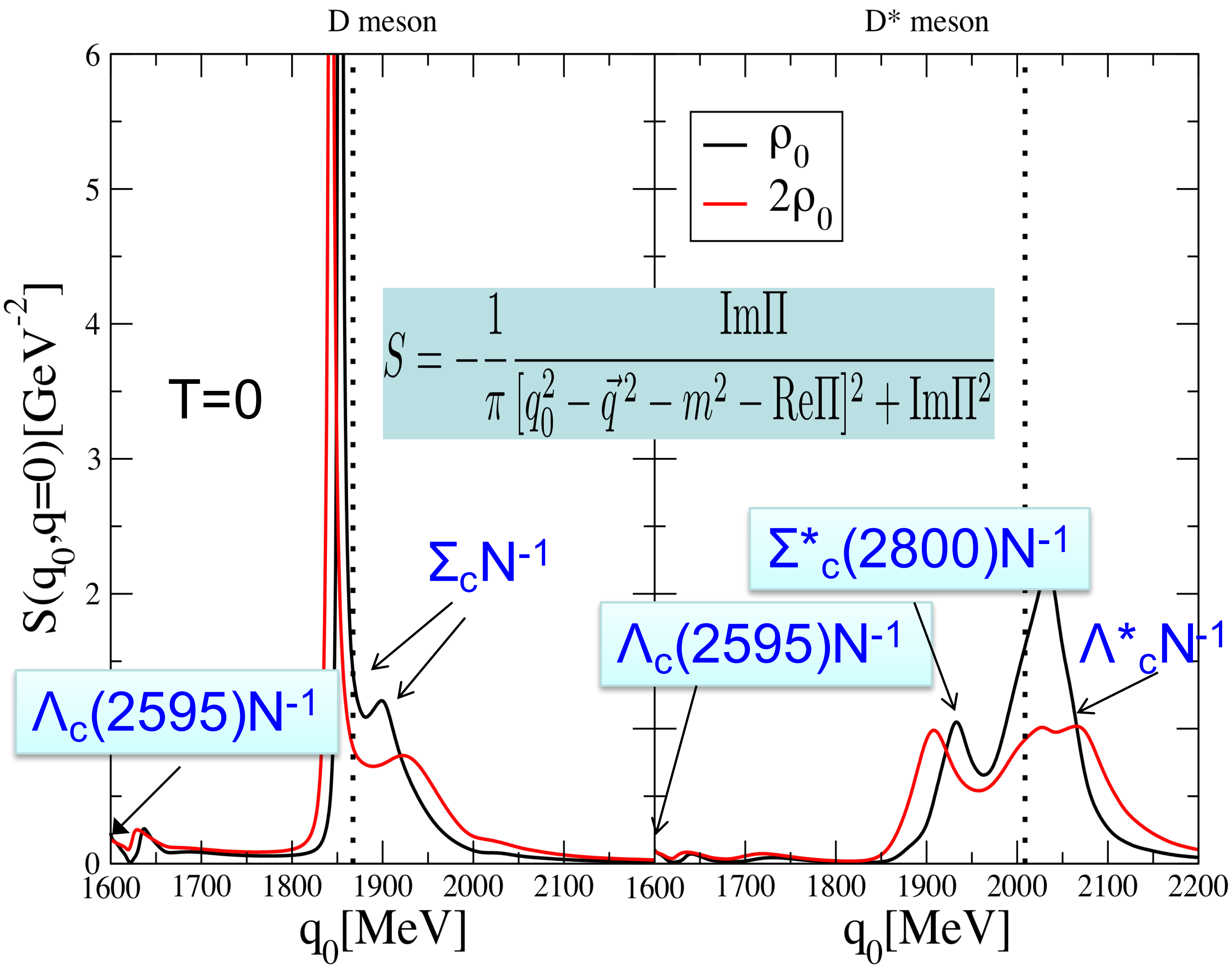
Dynamically-generated baryonic resonances in nuclear matter

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



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

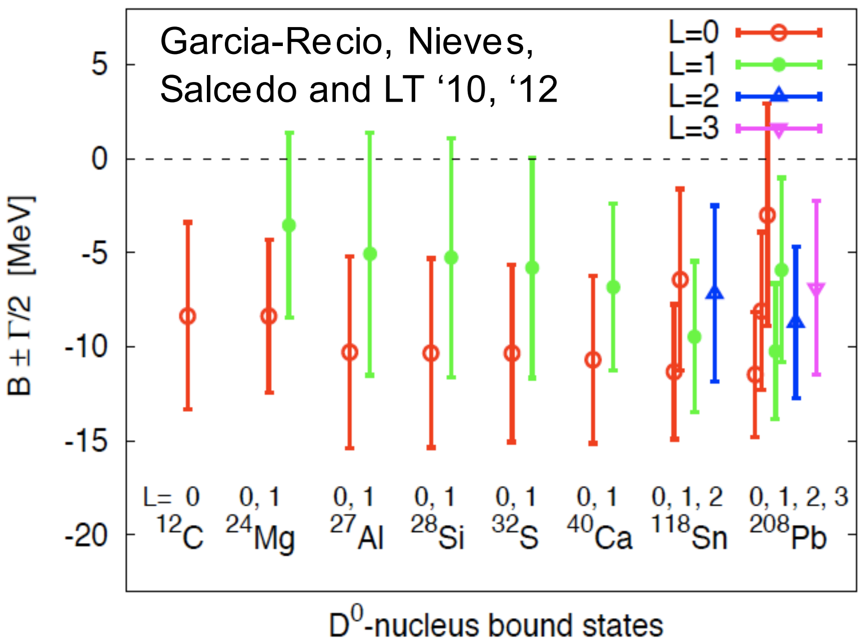
Initially predicted in ^{208}Pb within QMC model Tsushima et al. ‘99

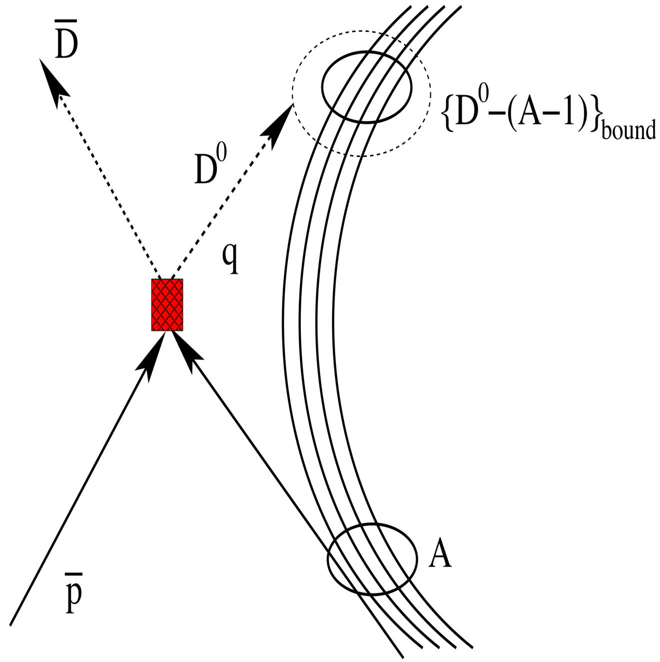
Within the self-consistent coupled-channel approach that incorporates HQSS

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

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

$$E = q^0 - m_D$$





- 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-Sekihara, Garcia-Recio, Nieves, Salcedo and LT '16

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

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

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

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

$$D^{*-} + A_Z \to \pi^0 + \left[A_Z - D^-\right]_b$$

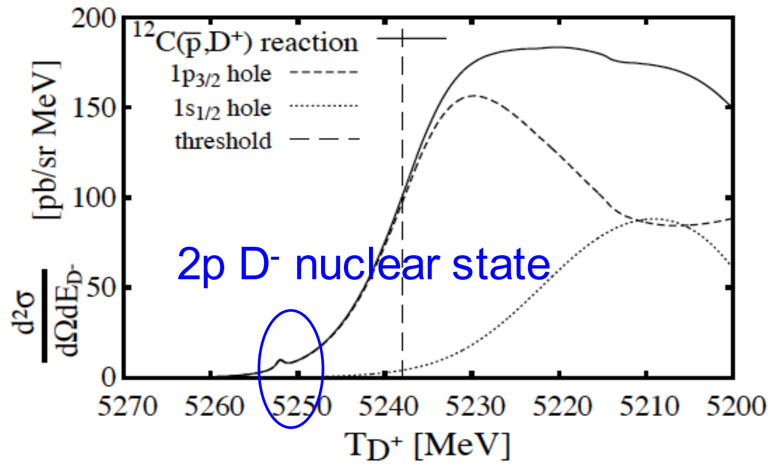


Figure 2: Formation spectrum for the $\bar{p} + {}^{12}\mathrm{C} \to \left[{}^{11}\mathrm{B} - \mathrm{D}^-\right] + \mathrm{D}^+$ reaction at $P_{\bar{p}} = 8\mathrm{GeV/c}$ and $\theta^{\mathrm{LAB}}_{D^+} = 0°$, as a function of the outgoing D^+ meson total energy. The partial contributions of some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

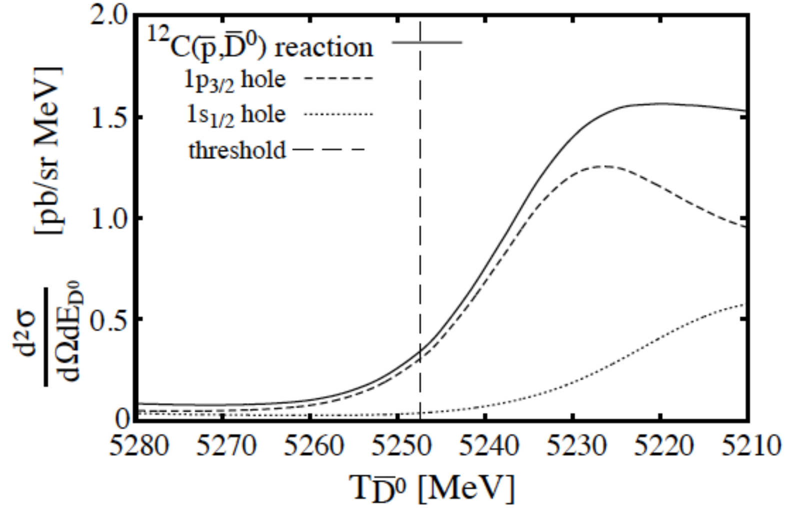


Figure 3: Same as in Fig. 2, but for the $\bar{p} + {}^{12}\mathrm{C} \to \left[{}^{11}\mathrm{B} - \mathrm{D}^0\right] + \bar{\mathrm{D}}^0$ reaction. The vertical dashed line indicates now the D^0 meson production threshold.

D meson propagation in dense hot matter

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

Fokker-Planck equation ($m_D >> m_{bath}$, $m_D >> T_{bath}$)

drag force — diffusion coefficient

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

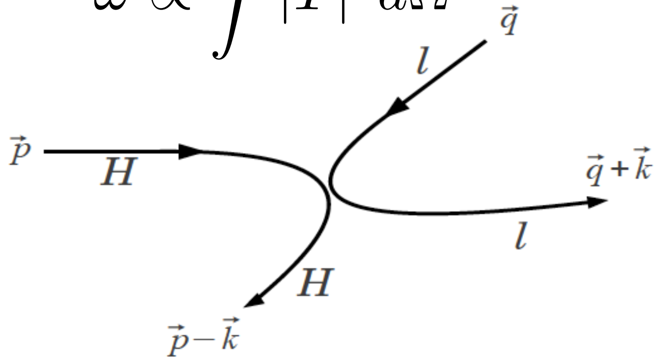
isotropic bath

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

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

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

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



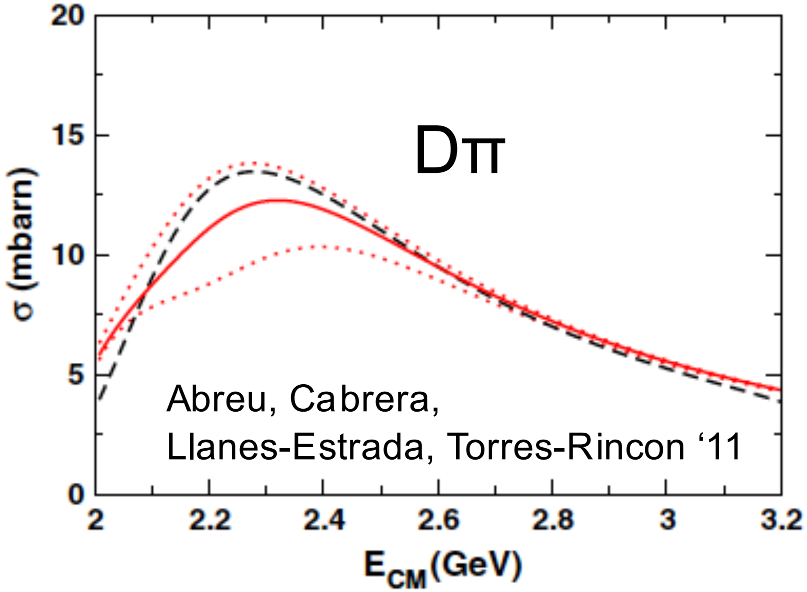
Previous works Laine '11; He, Fries, Rapp '11; Ghosh, Das, Sarkar, -eAlam '11

We need scattering amplitudes $|T|^2$ (first approximation: $|T|^2$ in free space)

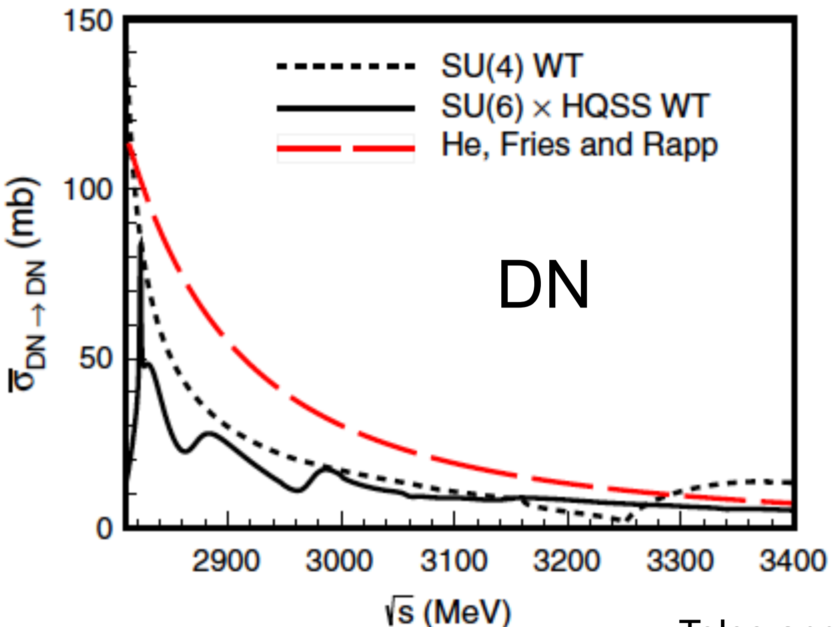
Abreu, Cabrera, Llanes-Estrada, Torres-Rincon '11; LT and Torres-Rincon '13

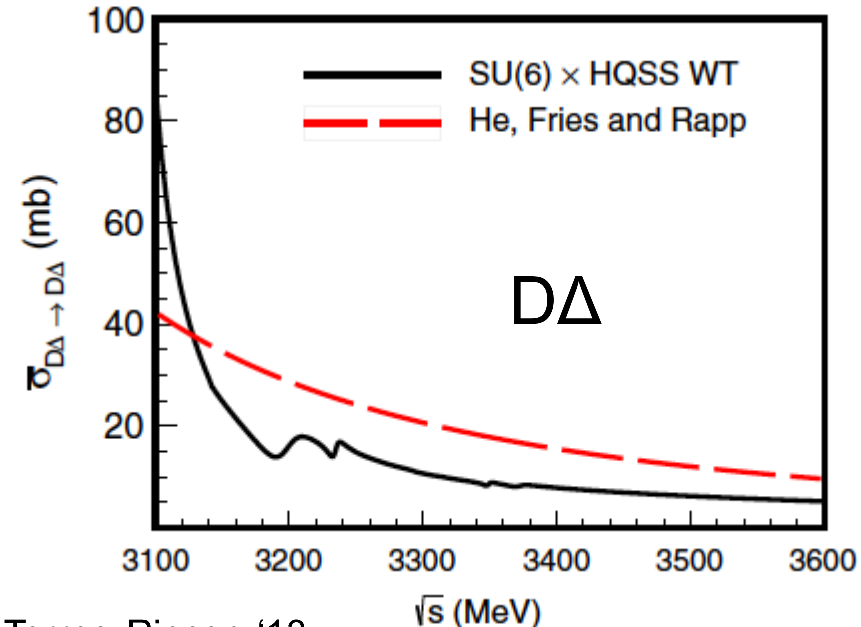
(Vacuum) cross sections for open charm with mesons and baryons

D-mesons with light mesons
(π, K, K, η)



D-mesons with baryons (N, Δ)

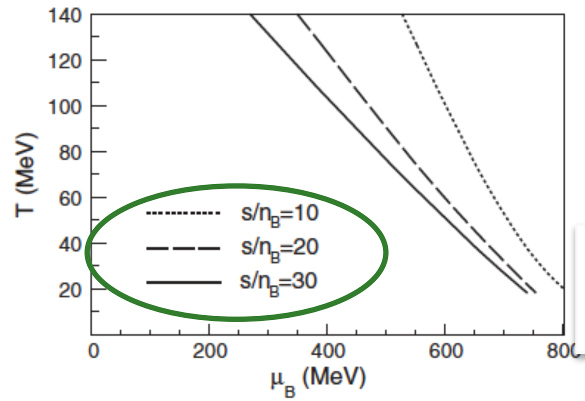




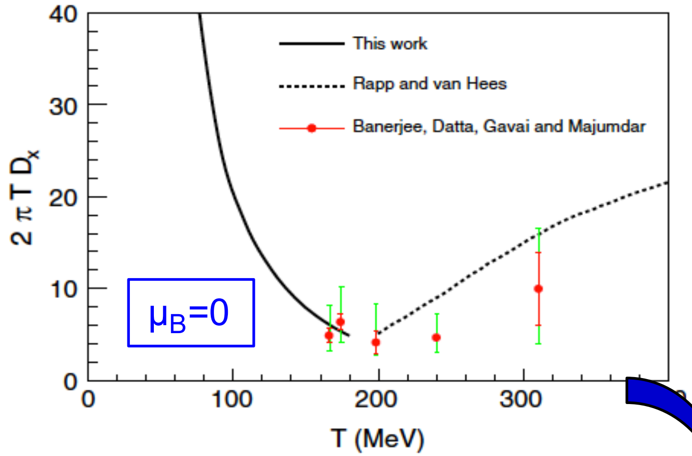
Tolos and Torres-Rincon '13

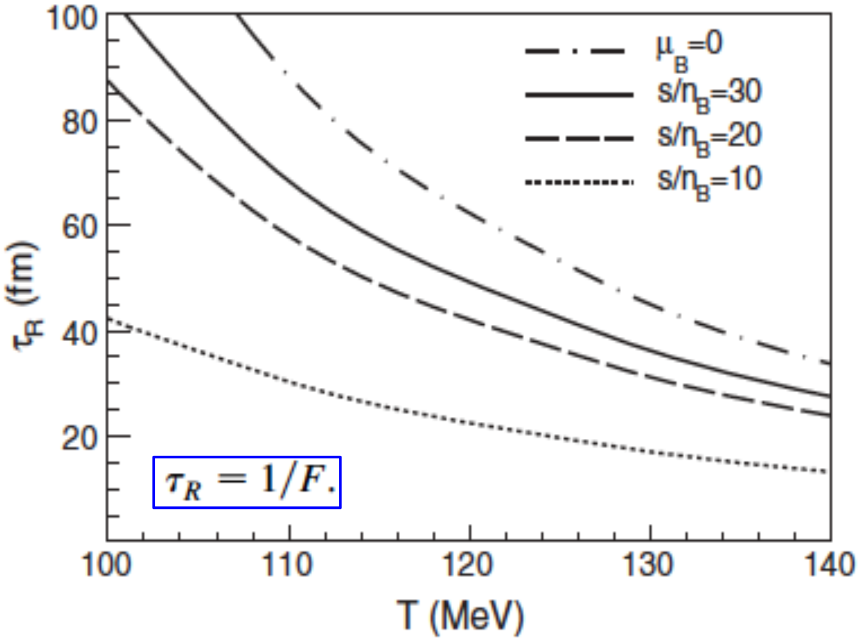
Some results for CBM@FAIR energies

LT and Torres-Rincon '13

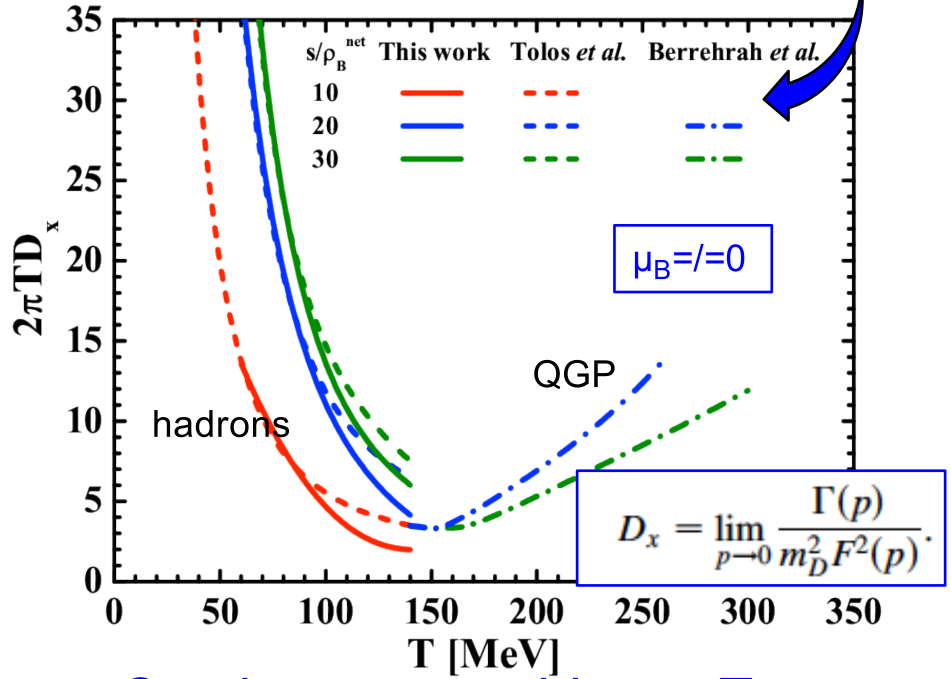


FAIR energies
5-40 AGeV





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



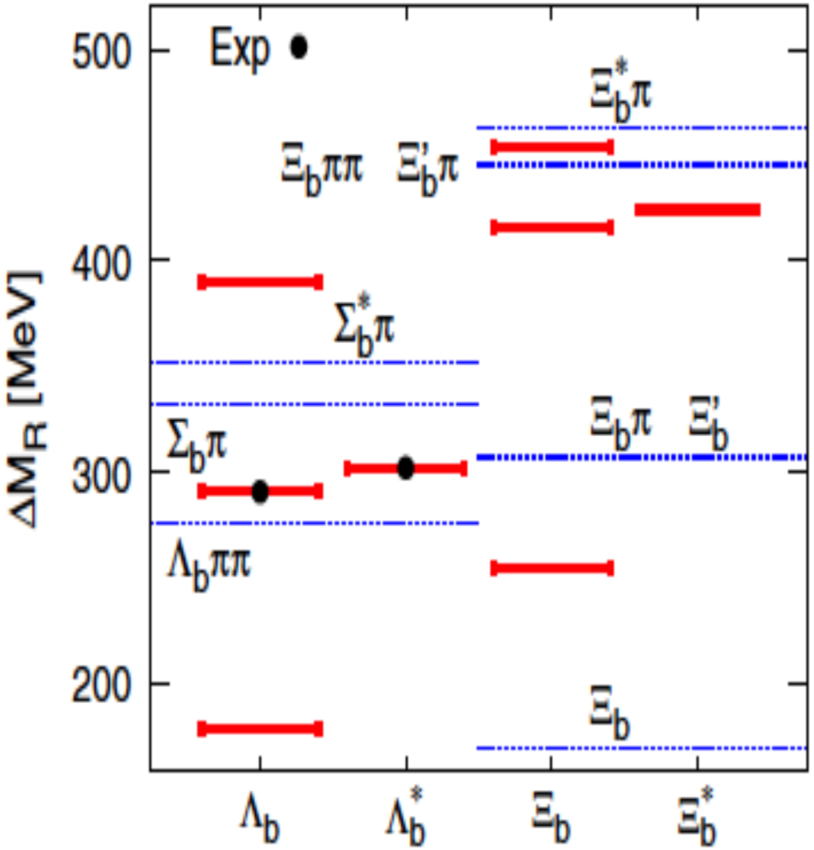
$$D_x = \lim_{p \to 0} \frac{\Gamma(p)}{m_D^2 F^2(p)}.$$

Continuous matching at T_c

Berrehrah et al '14; Ozvenchuk et al (LT) '14; Song et al (LT) '15

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

Beauty propagation in dense hot matter

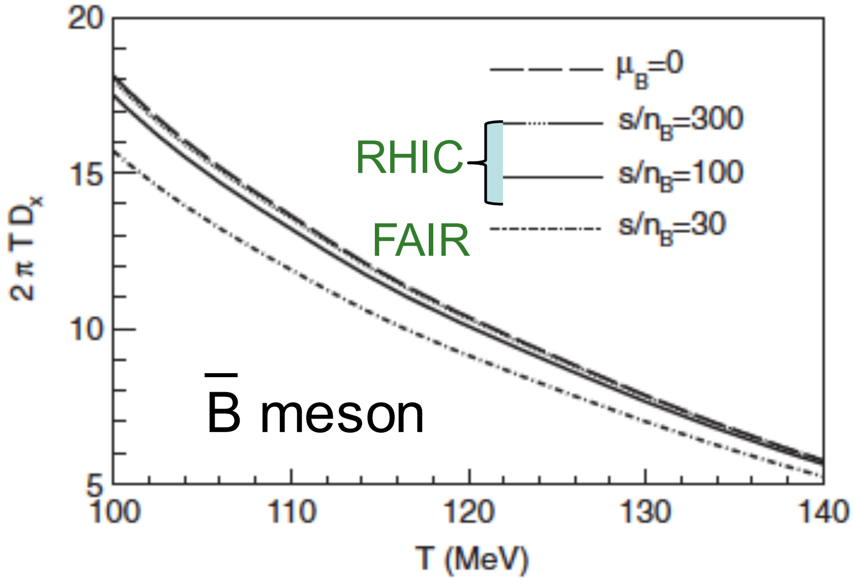
Fokker-Planck equation

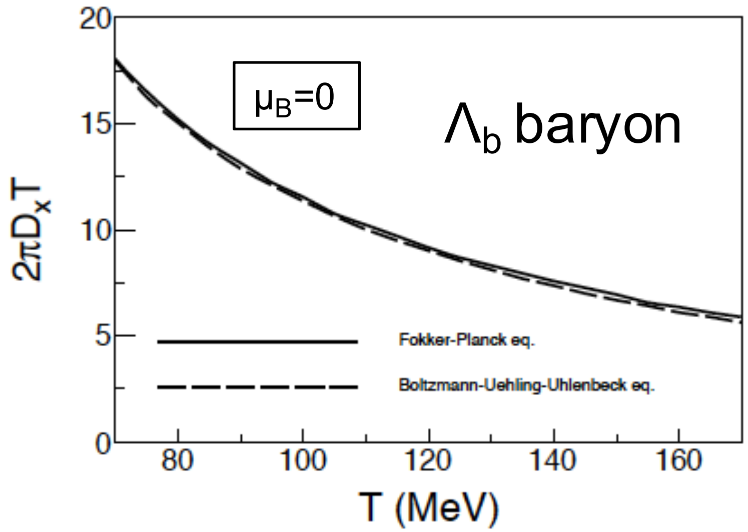
$$\frac{\partial f(t,\mathbf{p})}{\partial t} = \frac{\partial}{\partial p_i}\left\{F_i(\mathbf{p}) f(t,\mathbf{p}) + \frac{\partial}{\partial p_j}\left[\Gamma_{ij}(\mathbf{p}) f(t,\mathbf{p})\right]\right\},$$

drag force — diffusion coefficient

Results from FAIR to RHIC energies

Torres-Rincon, LT and Romanets '14; LT, Torres-Rincon and Das '16; Song et al (LT) '16





- Results insensitive to trajectory for high s/n_B:
prediction for behaviour of hadronic medium at RHIC energies
- Similar behaviour of diffusion coefficient for $\bar{B}$ meson and Λ_b

Summary

- it is an exciting moment

- moving from the light to the heavy sector

- a lot of theoretical effort is needed
(how to construct a reliable effective theory that implements the correct symmetries)

- but in close connection to experiments/lattice
(how to provide feedback between theory and experiments/lattice: spectroscopy of excited states, spectra of meson-nucleus, transport coefficients,..)

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