Heavy hadrons (charm, beauty) in nuclei

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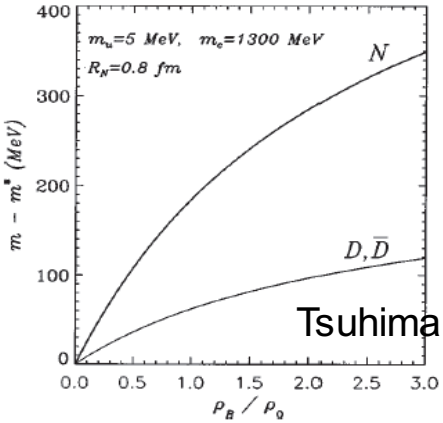
International workshop on
"Hadron structure and interaction in dense matter"
(Satellite workshop of QNP2018)
KEK Tokai campus, November 11-12, 2018

Charm in Matter

QMC model

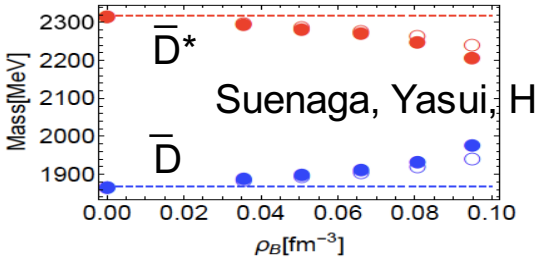
exchange of ω, ρ, σ mesons among quarks in hadron bag



Tsushima, Thomas, Krein, Sibirtsev, Fountoura..

Tsuhima et al '98

Chiral models: MF/RHF/Parity Doublet



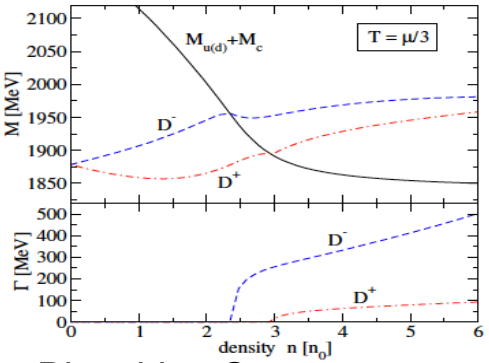
Suenaga, Yasui, Harada '17

Relativisitic approaches that include charmed mesons

Mishra, Kumar, Harada, Suenaga Sasaki, Yasui, Yamazaki..

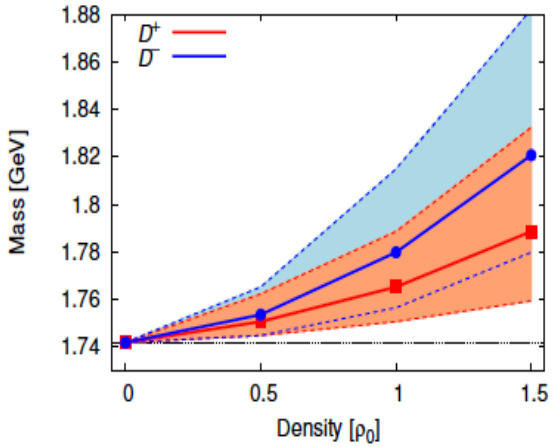
NJL model

SU(4) NJL model with Polyakov loop



Blaschke, Costa and Kalinovsky '12

QCD sum-rule

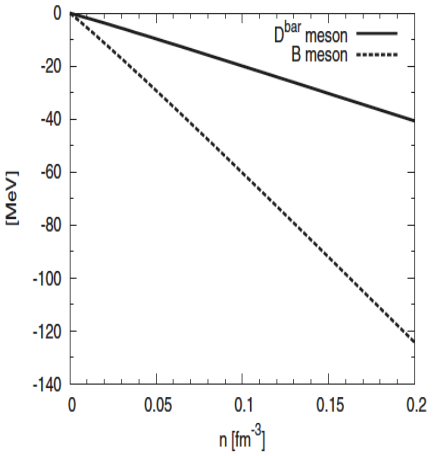


Suzuki, Gubler and Oka '16

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

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

π exchange with HQS



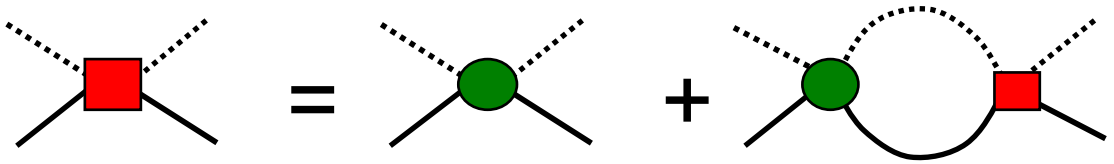
heavy meson - nucleon interaction mediated by π exchange implementing HQS

Yasui and Sudoh '13

Reviews: LT '13; Hosaka, Hyodo, Sudoh,Yamaguchi, Yasui '17

Unitarized theory in matter:
selfconsistent coupled-channel procedure

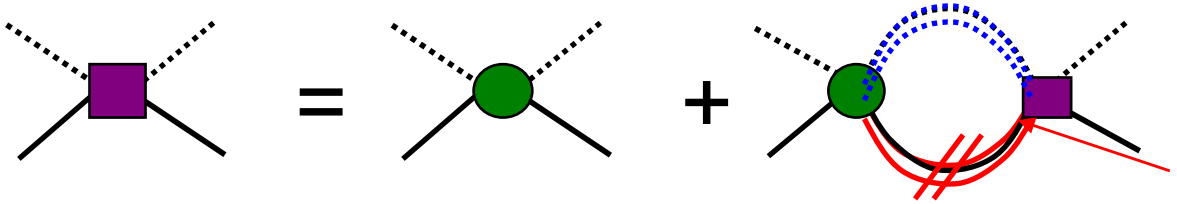
Free space



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

meson dressing

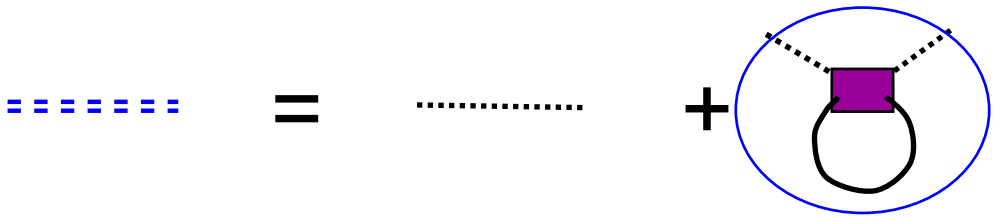
Medium



Pauli blocking and baryon dressing

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

Dressed meson:



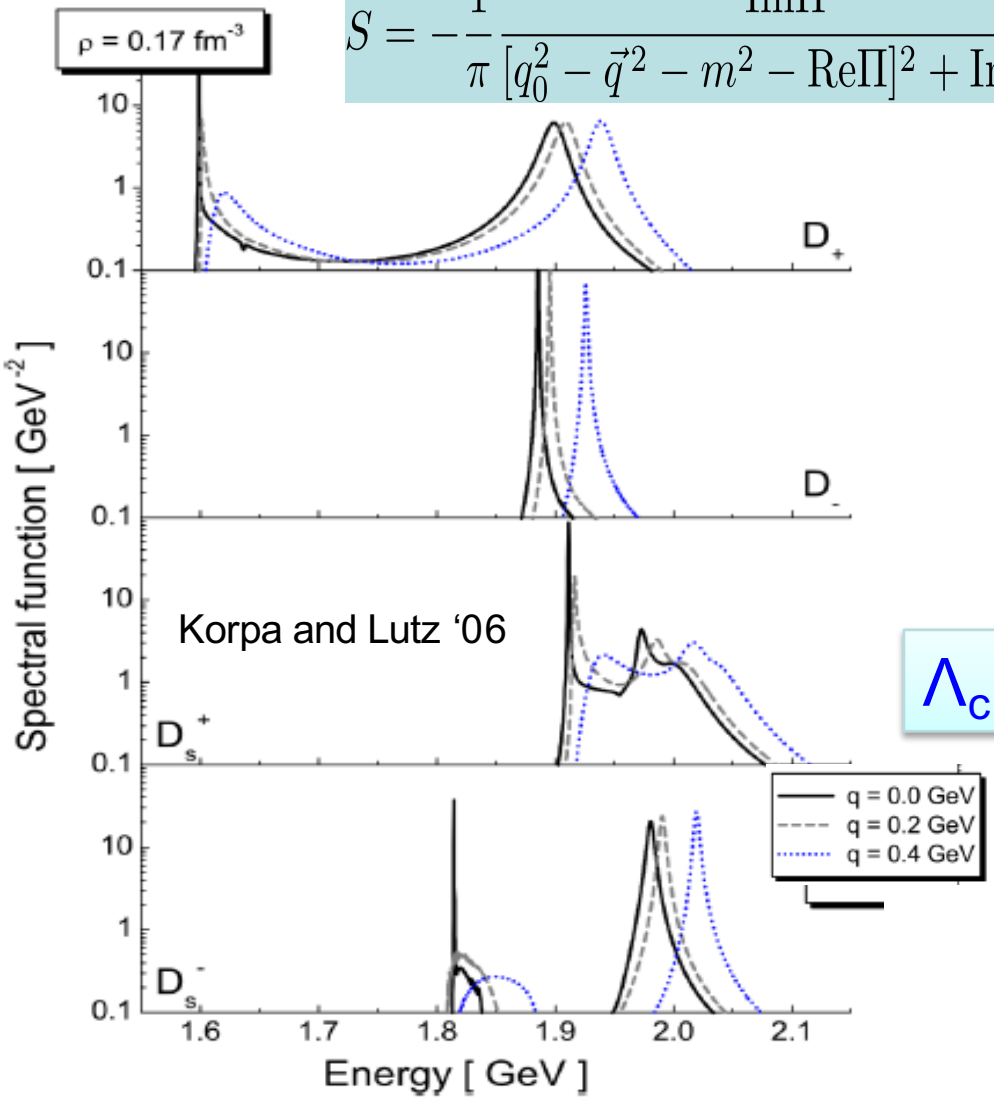
Π self-energy

Unitarized theory in matter

selfconsistent coupled-channel procedure

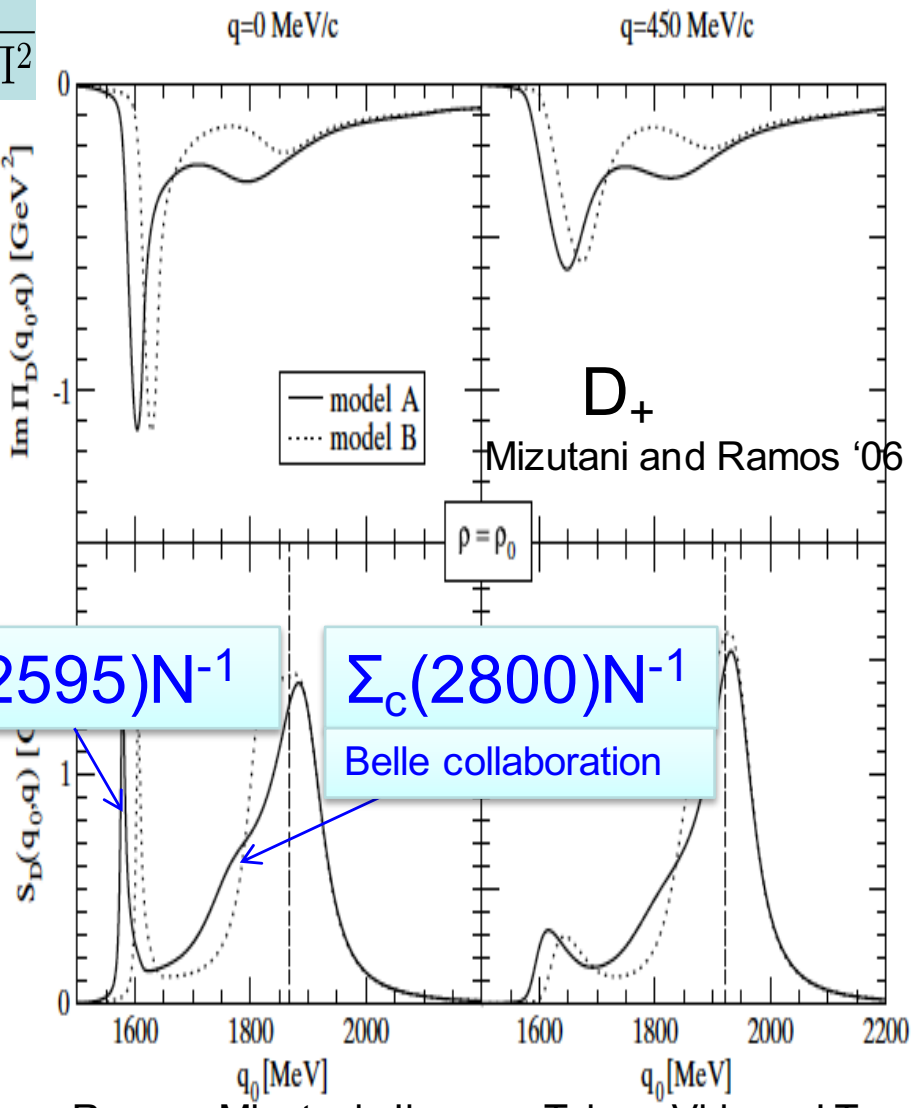
(bare interaction saturated by t-channel vector-meson exchange)

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



Korpa and Lutz '06

Lutz, Korpa, Hofmann..



D_+

Mizutani and Ramos '06

$\Lambda_c(2595)N^{-1}$

$\Sigma_c(2800)N^{-1}$

Belle collaboration

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

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

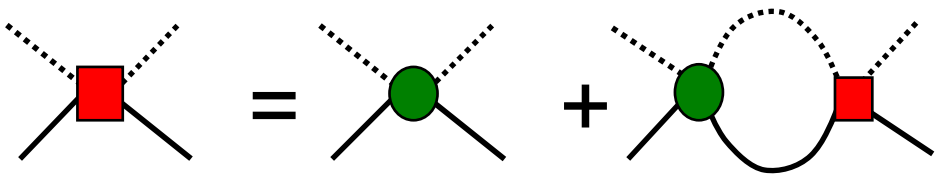
HQSS*: spin interactions vanish for infinitely massive quarks

*Isgur, Wise, Manohar, Neubert

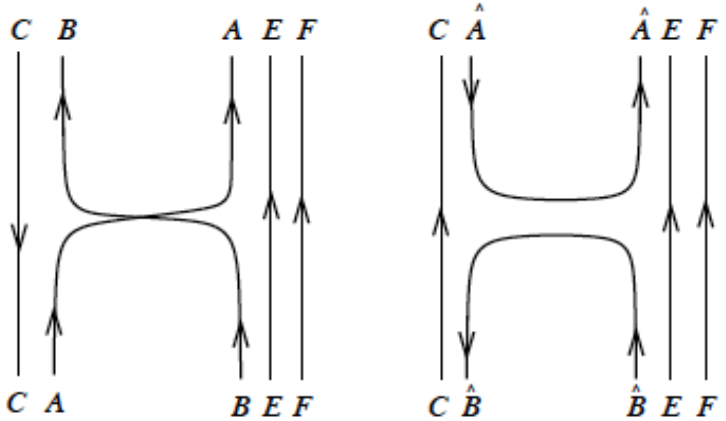
To construct a model for four flavors for pseudoscalar and vector mesons as well as $1/2^+$ and $3/2^+$ baryons that incorporates HQSS in the charm sector: extended WT interaction that fulfills SU(6)xHQSS and it is consistent with chiral symmetry in the light sector

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

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



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



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

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

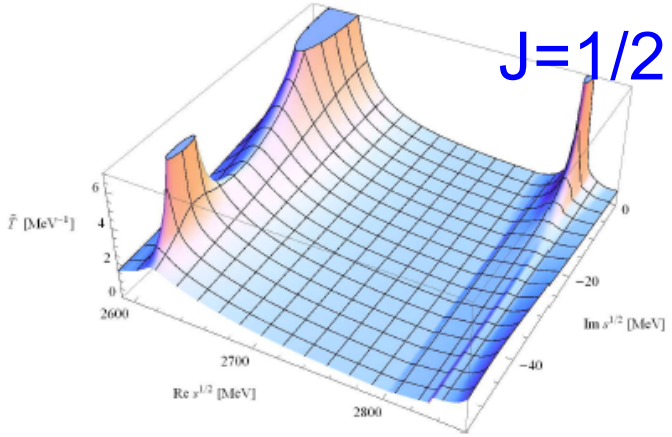
Garcia-Recio et al.'09;
Romanets et al. '12

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

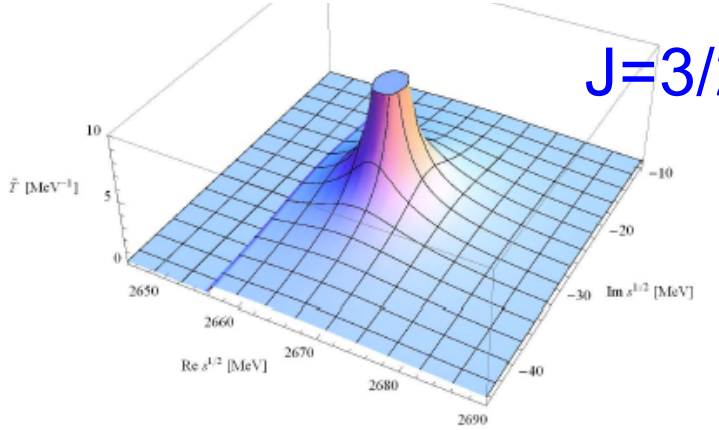
coupling constant

mass and width

J=1/2



J=3/2

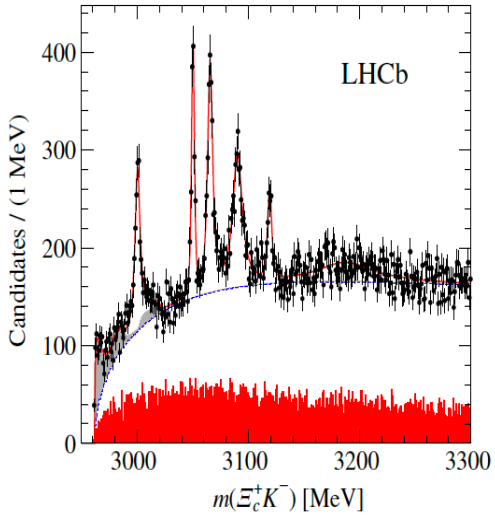


SU(8) irrep	SU(6) irrep	SU(3) irrep	M_R	Γ_R	Couplings to main channels	Status PDG	J
168	$\mathbf{15}_{2,1}$	$\mathbf{3}^*_2$	2617.3	89.8	$g_{\Sigma_c\pi} = \mathbf{2.3}$, $g_{ND} = 1.6$, $g_{ND^*} = 1.4$, $g_{\Sigma_c\rho} = 1.3$		1/2
168	$\mathbf{15}_{2,1}$	$\mathbf{3}^*_4$	2666.6	53.7	$g_{\Sigma_c^*\pi} = \mathbf{2.2}$, $g_{ND^*} = 2.0$, $g_{\Sigma_c\rho} = 0.8$, $g_{\Sigma_c^*\rho} = 1.3$	$\Lambda_c(2625)$ ***	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 $\Lambda_c(2625)$

Ω_c :
C=1, S=-2, I=0

5 states seen by LHCb
First four seen by Belle



Resonance	Mass (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$
		<1.2 MeV, 95% C.L.
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$
		<2.6 MeV, 95% C.L.
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$
$\Omega_c(3066)^0_{fd}$		
$\Omega_c(3090)^0_{fd}$		
$\Omega_c(3119)^0_{fd}$		

Aaij et al '17

Renormalization with one subtraction ➡ Common cutoff regularization

$$G_i(s) = \overline{G}_i(s) - (1-x)\overline{G}_i(\mu^2) + x G_i^{\Lambda}(s_{i+})$$

$\Lambda = 1090$ MeV

Name	M_R (MeV)	Γ_R (MeV)	J
a	2810.9	0	1/2
b	2814.3	0	3/2
c	2884.5	0	1/2
d	2941.6	0	1/2
e	2980.0	0	3/2

Romanets, LT, Garcia-Recio, Nieves, Salcedo, Timmermans '12

Mass too low!

Name	M_R (MeV)	Γ_R (MeV)	J	M_R^{exp}	Γ_R^{exp}
a	2963.95	0.0	1/2	–	–
c	2994.26	1.85	1/2	3000.4	4.5
b	3048.7	0.0	3/2	3050.2	0.8
d	3116.81	3.72	1/2	3119.1/ 3090.2	1.1/ 8.7
e	3155.37	0.17	3/2	–	–

Nieves, Pavao and LT '18

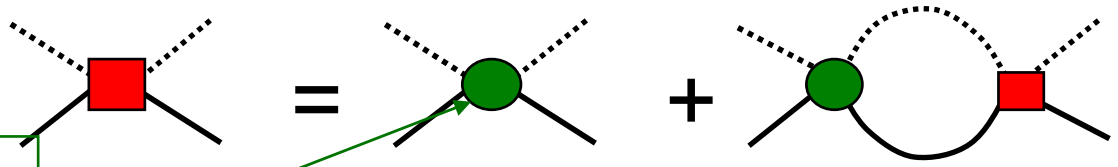
cutoff dependence: a maximum number of three states can be identified

Charmed hadrons in matter

Unitarized theory in matter:

selfconsistent coupled-channel procedure

Free space

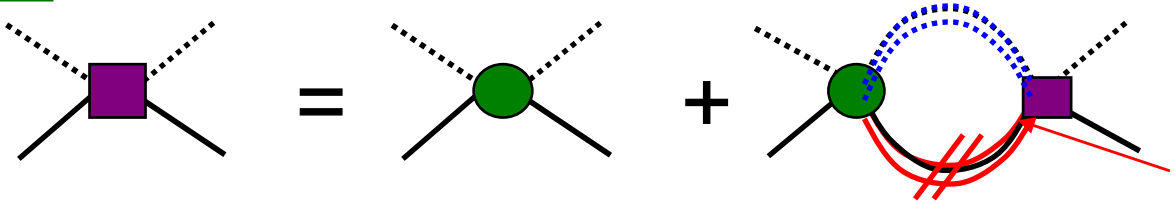


potential from extended WT interaction that respect HQSS

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

meson dressing

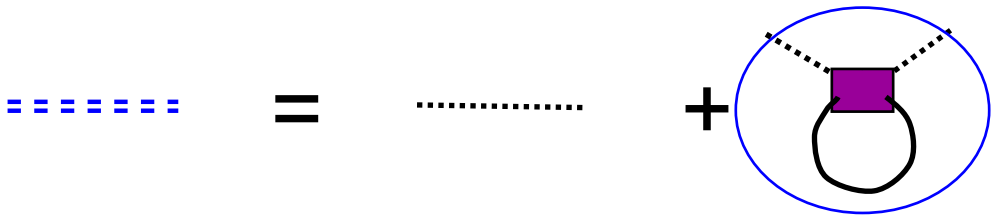
Medium



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

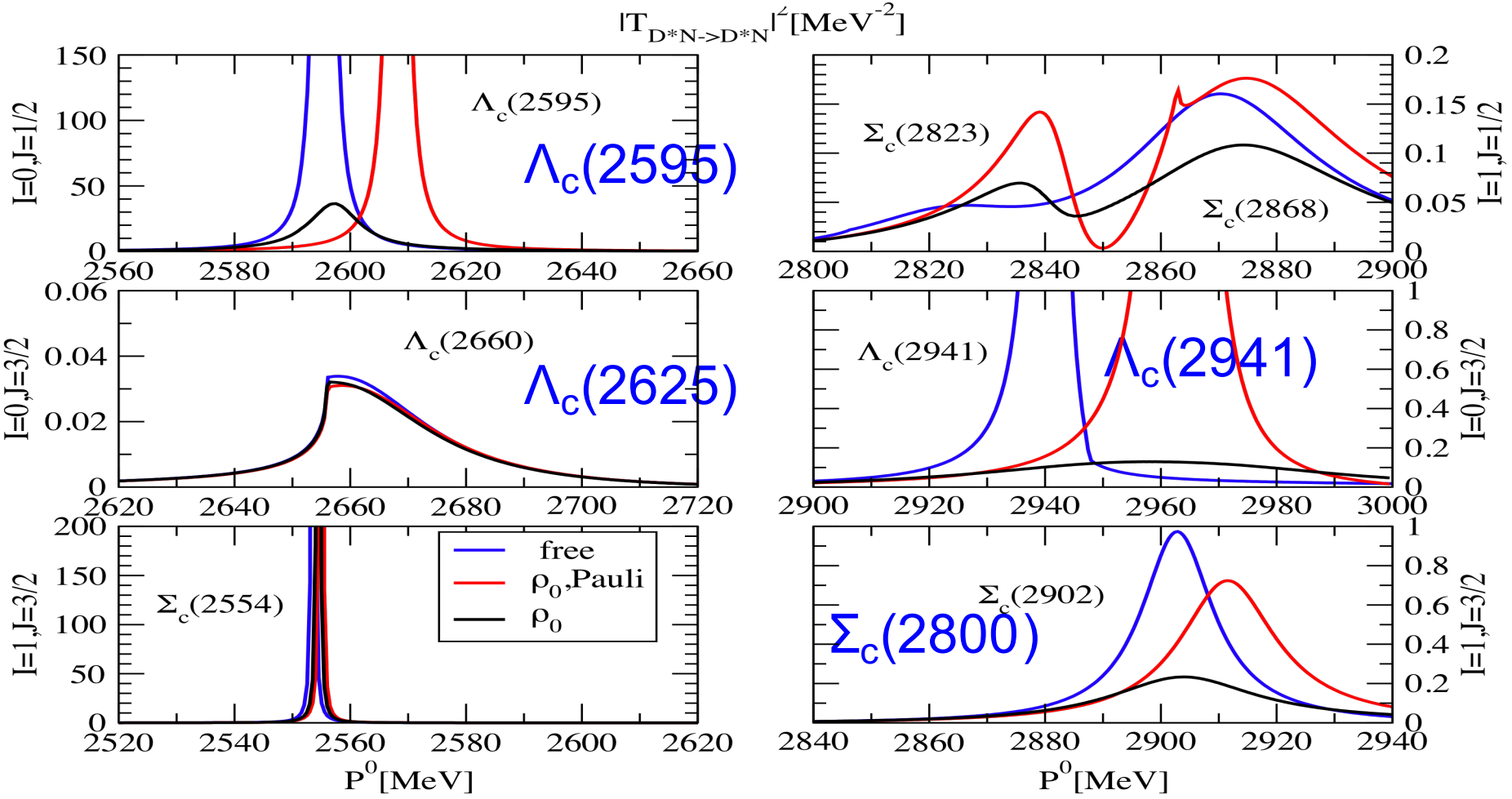
PDG (C=1,S=0,I=0/1)
no ground states

Resonance	$I(J^P)$	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
$\Lambda_c(2860)$	$0(3/2^+)$	$2856.1 + 2.3 - 6.0$	$68 + 12 - 22$
$\Lambda_c(2880)$	$0(5/2^+)$	2881.63 ± 0.24	$5.6 + 0.8 - 0.6$
$\Lambda_c(2940)$	$0(3/2^-)$	$2939.6 + 1.3 - 1.5$	$20 + 6 - 5$
$\Sigma_c(2800)^{++}$	$1(?^?)$	$2801 + 4 - 6$	$75 + 22 - 17$
$\Sigma_c(2800)^{+}$	$1(?^?)$	$2792 + 14 - 5$	$62 + 60 - 40$
$\Sigma_c(2800)^{0}$	$1(?^?)$	$2806 + 5 - 7$	$72 + 22 - 15$

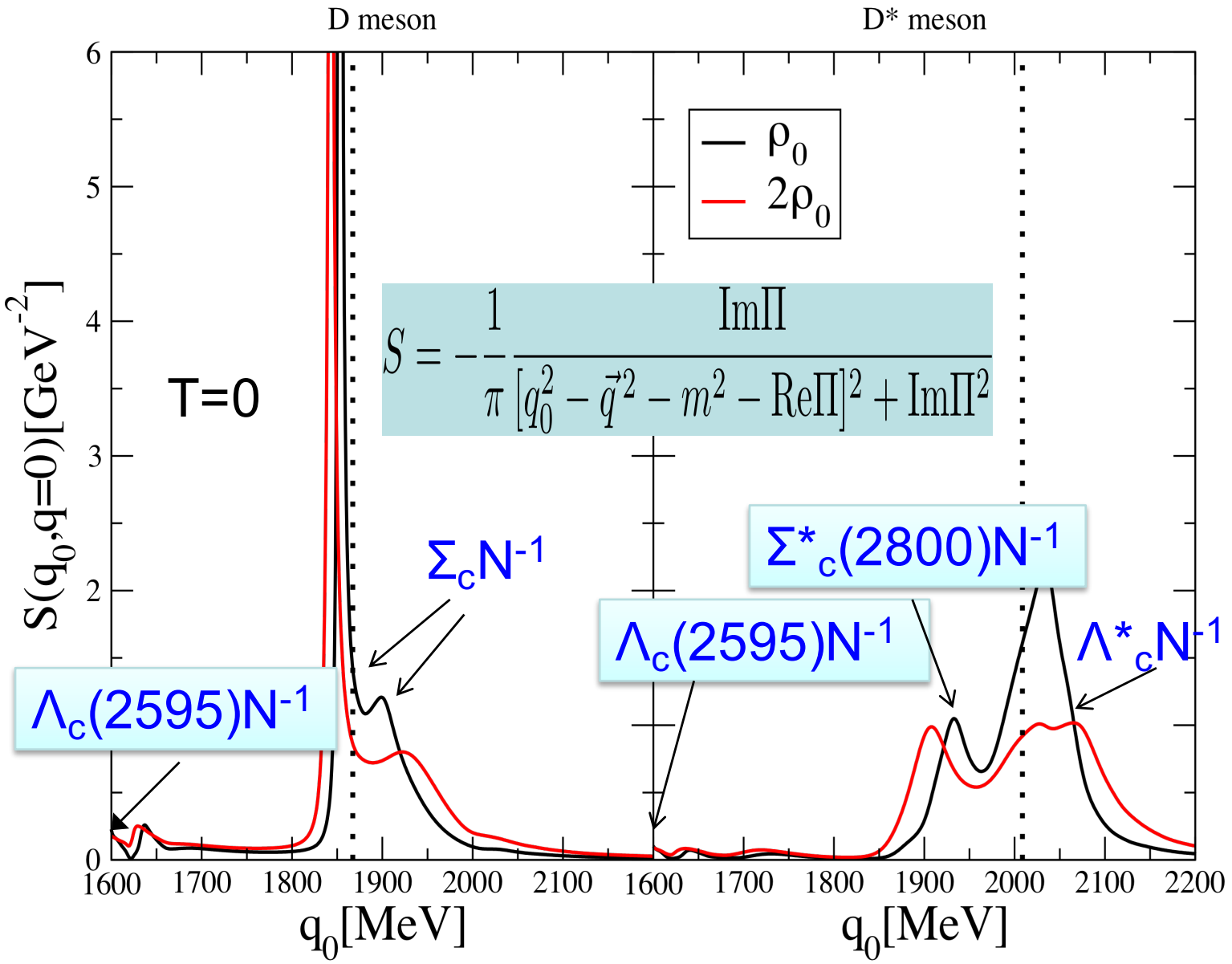
Dynamically-generated baryonic resonances in nuclear matter

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



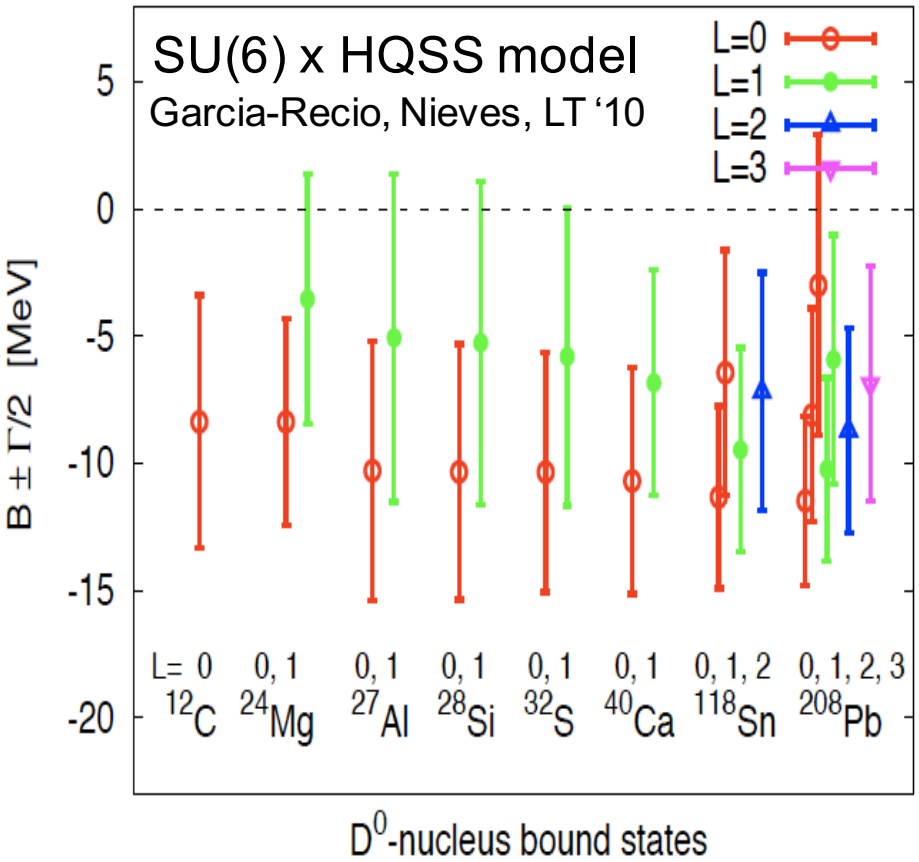
Simultaneous calculation of D and D* self-energies

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

Solving Schroedinger or Klein-Gordon equation with
- potential from QMC model
- potential from SU(6) x HQSS model
- potential from π exchange model with HQS

D^0 and D^+



- SU(6) x HQSS model: weakly bound D^0-nucleus states with important widths in contrast to

QMC model ^{208}Pb

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

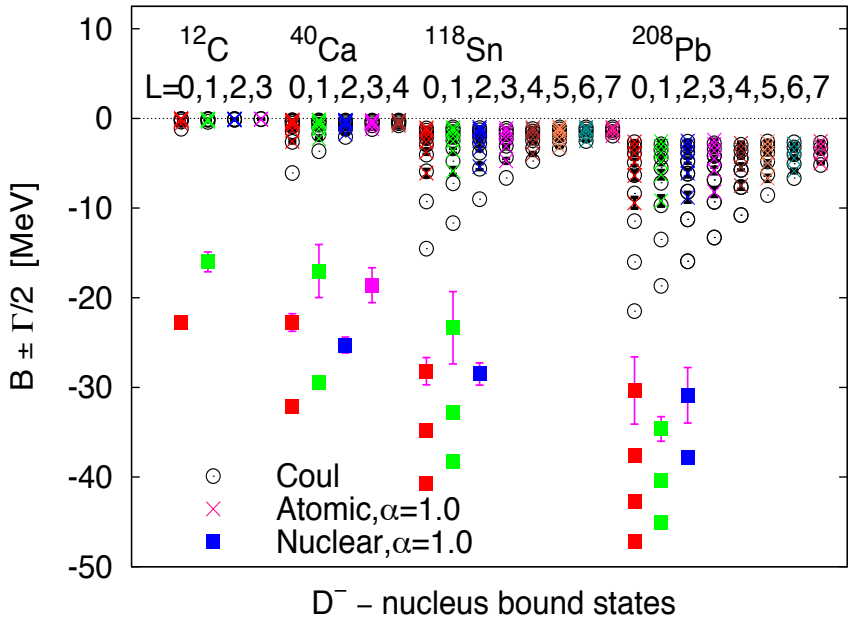
Tsushima et al. '99
Krein et al '17 (review)

- SU(6) x HQSS model:
D^+ does not bind

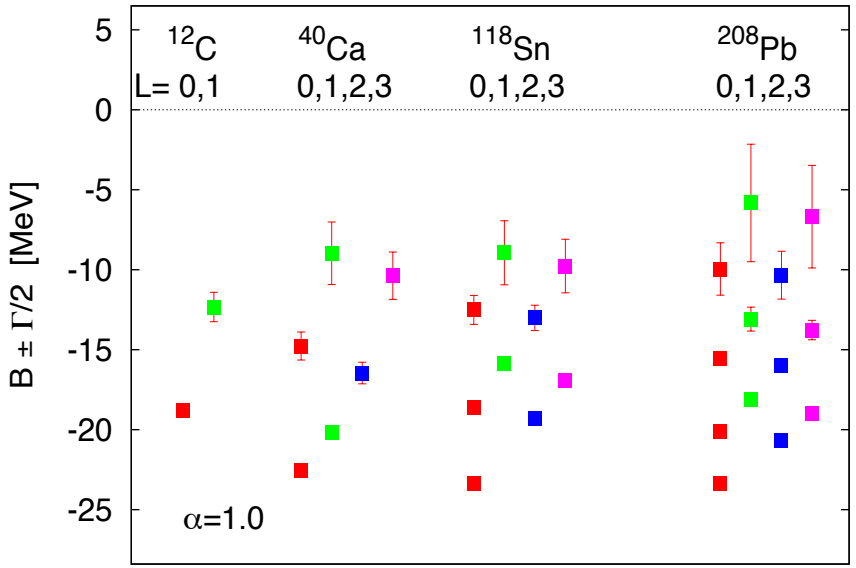
D^- and $\bar{D}^0$

SU(6) x HQSS model:

Garcia-Recio, Nieves, Salcedo and LT '12



D^- – nucleus bound states



$\bar{D}_0$ – nucleus bound states

QMC model

Tsushima, Lu, Thomas, Saito and Landau ' 99

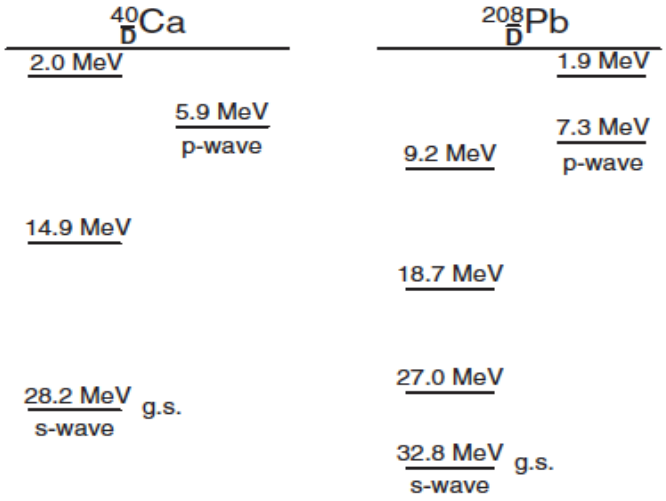
Krein, Thomas and Tsushima '17 (review)

^{208}Pb

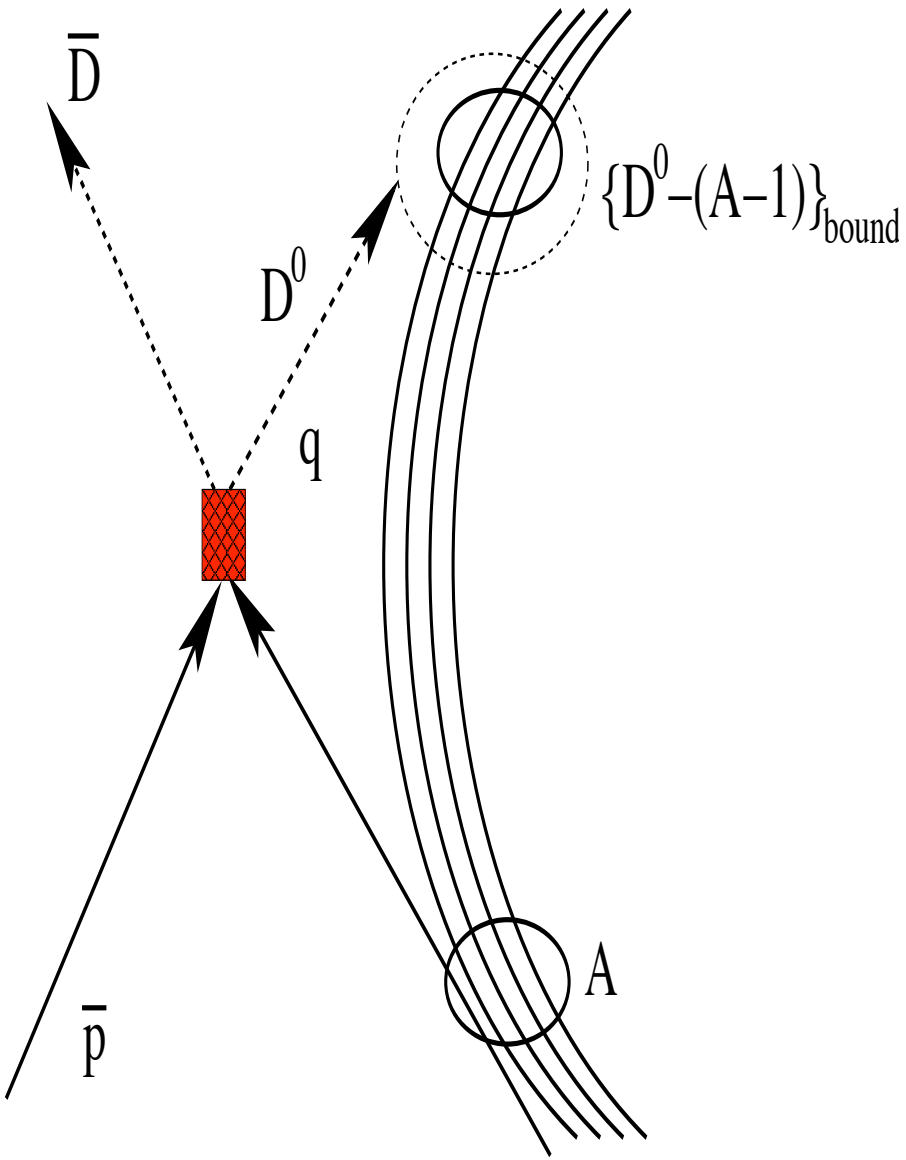
State	$D^-(\tilde{V}^q_\omega)$	$D^-(V^q_\omega)$	$D^-(V^q_\omega$, no Coulomb)	$\bar{D}^0(\tilde{V}^q_\omega)$	$\bar{D}^0(V^q_\omega)$
$1s$	−10.6	−35.2	−11.2	Unbound	−25.4
$1p$	−10.2	−32.1	−10.0	Unbound	−23.1
$2s$	−7.7	−30.0	−6.6	Unbound	−19.7

π exchange model with HQS

Yasui and Sudoh '13

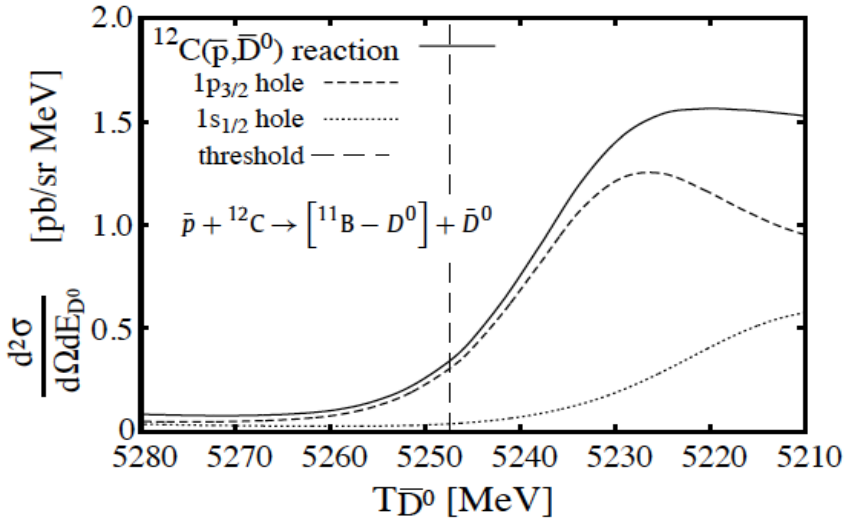


Experimental observation is, though, a difficult task (PANDA, J-PARC?)



Hiroaki Ohnishi's talk

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



Large momentum transfer (about 1 GeV/c) makes any structure due to bound states not noticeable.

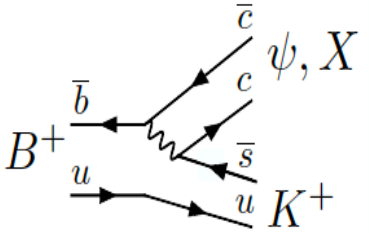
Need of reactions with lower momentum transfer, such as

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

Charm resonances in matter: X(3872)

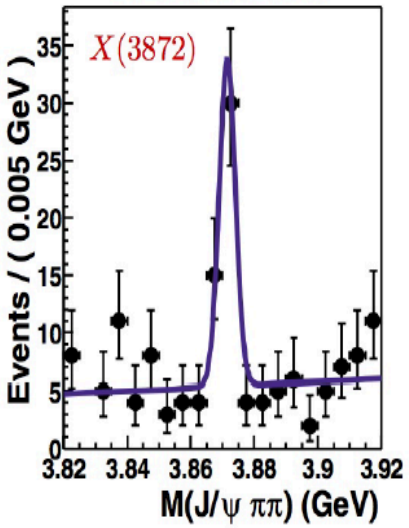
as $D\bar{D}^*$ molecule

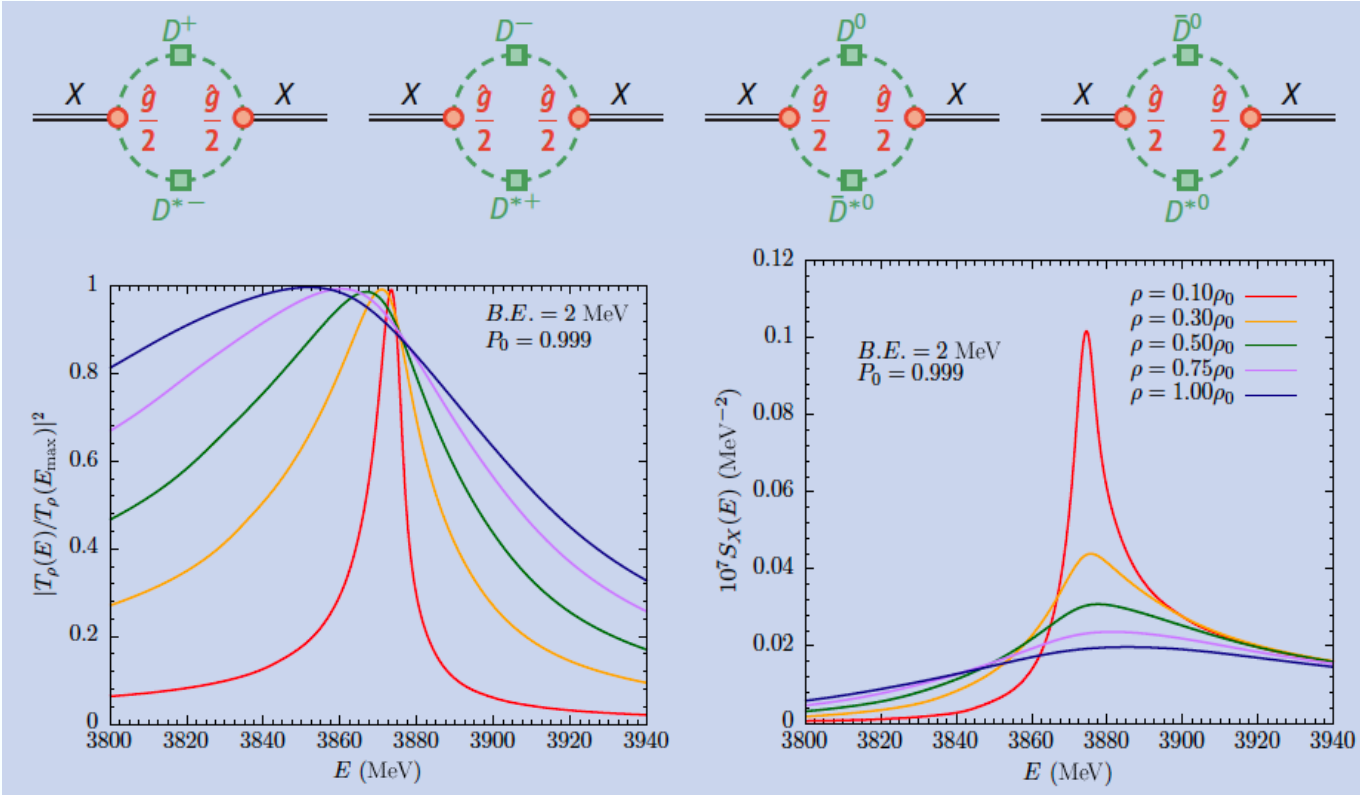
B decays: *Belle, BaBar, LHCb, etc.*



$B \to KX; X \to \pi^+\pi^- J/\psi$ at Belle

PRL91,262001 (2003)





	$P_0 = 0.999$	
ρ/ρ_0	E_{max} (MeV)	E_{qp} (MeV)
0.10	3873.3	3878.0
0.30	3870.8	—
0.50	3866.9	—
0.75	3860.3	—
1.00	3851.9	—

- Spectral function:
$$S_X^{(\rho)}(E) = -\frac{1}{\pi}\mathrm{Im}\Delta_\rho(E) = -\frac{1}{\pi}\frac{\mathrm{Im}\Pi_\rho(E)}{(E^2 - m_0^2 - \mathrm{Re}\Pi_\rho(E))^2 + (\mathrm{Im}\Pi_\rho(E))^2}$$
- Quasi-particle peak:
$$E_{qp}^2 - m_0^2 - \mathrm{Re}\Pi(E_{qp}) = 0.$$

Albaladejo, Nieves and LT, in preparation

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

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

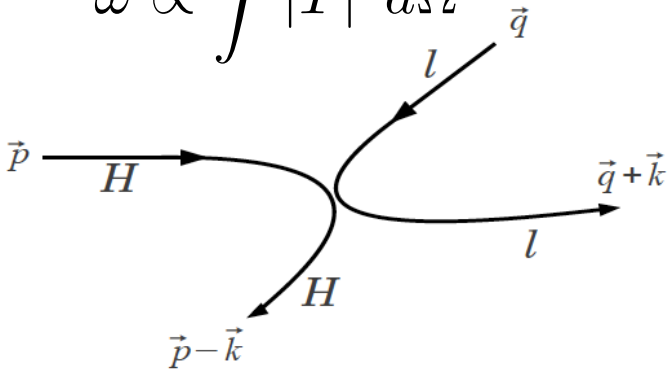
isotropic bath

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

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

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

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



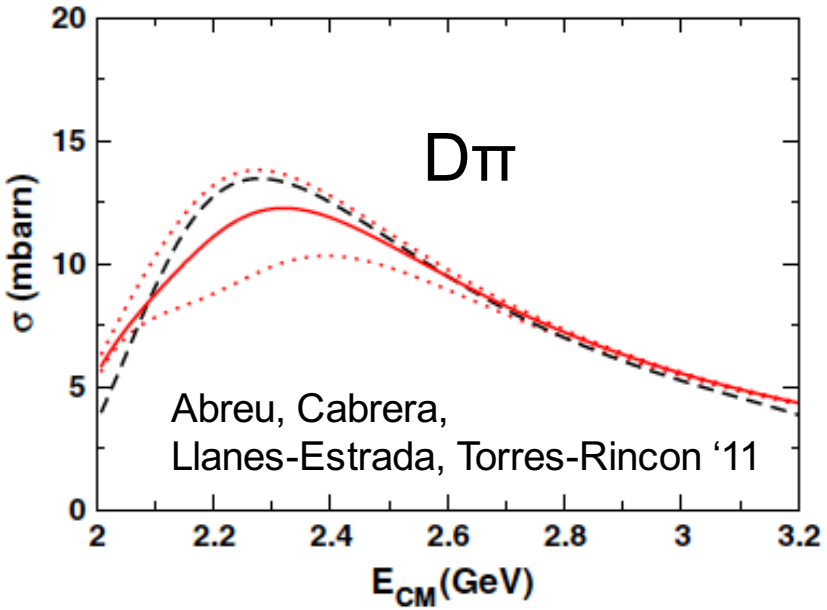
Previous works Laine '11; He, Fries, Rapp '11; Ghosh, Das, Sarkar, -eAlam '11

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

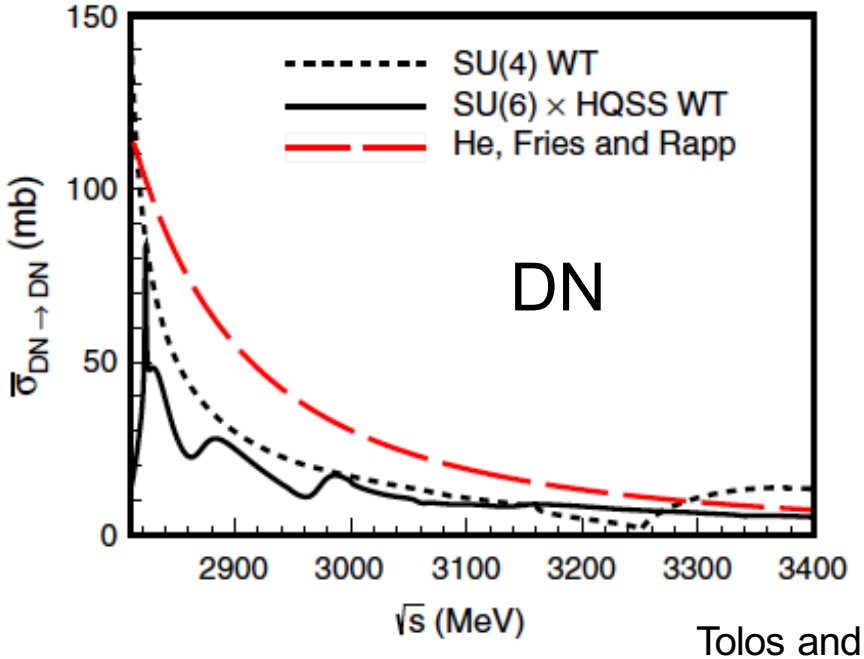
Abreu, Cabrera, Llanes-Estrada, Torres-Rincon '11; LT and Torres-Rincon '13

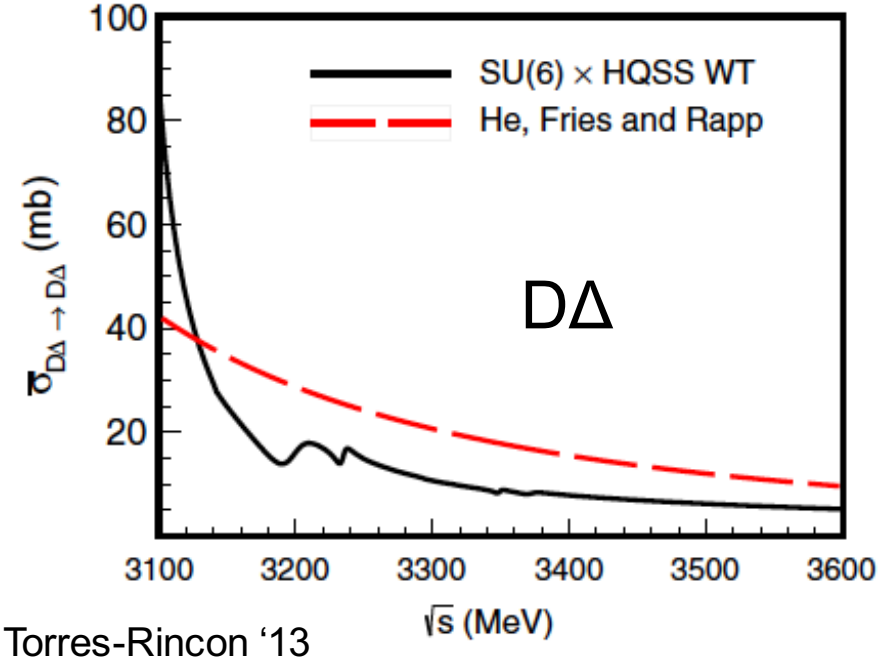
(Vacuum) cross sections for open charm with mesons and baryons

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



D-mesons with baryons (N, Δ)

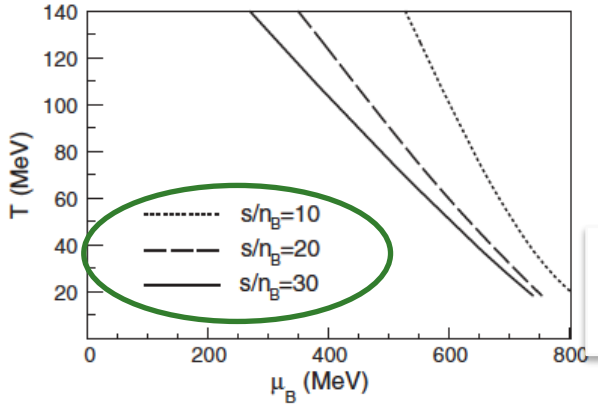


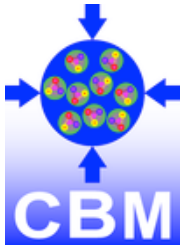


Tolos and Torres-Rincon '13

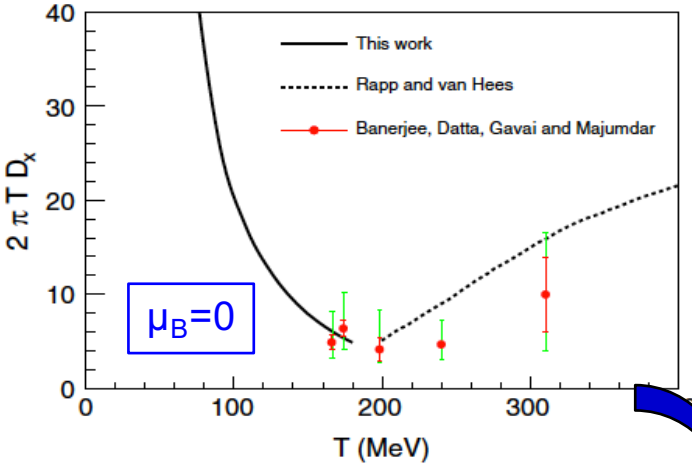
Some results for CBM@FAIR energies

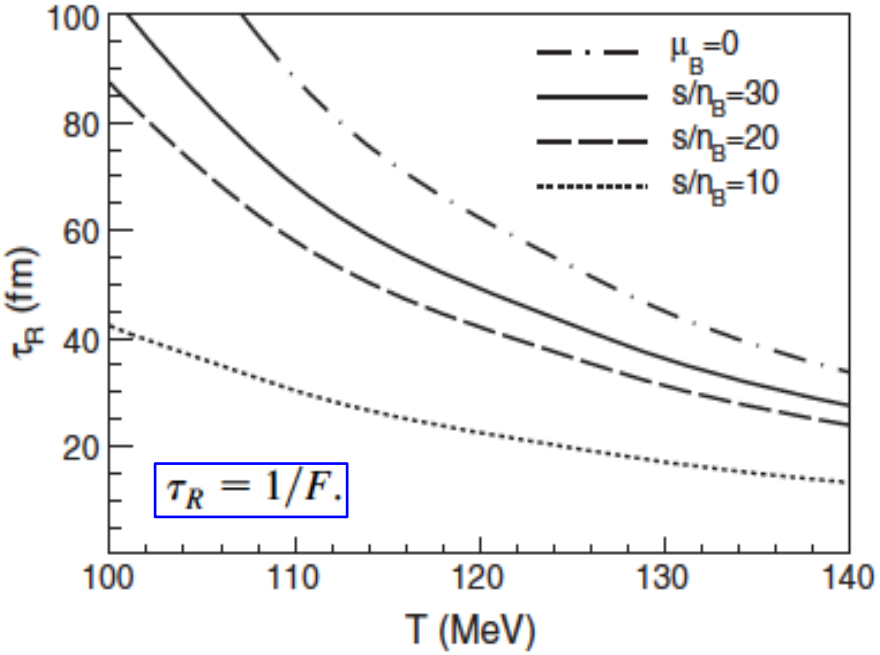
LT and Torres-Rincon '13



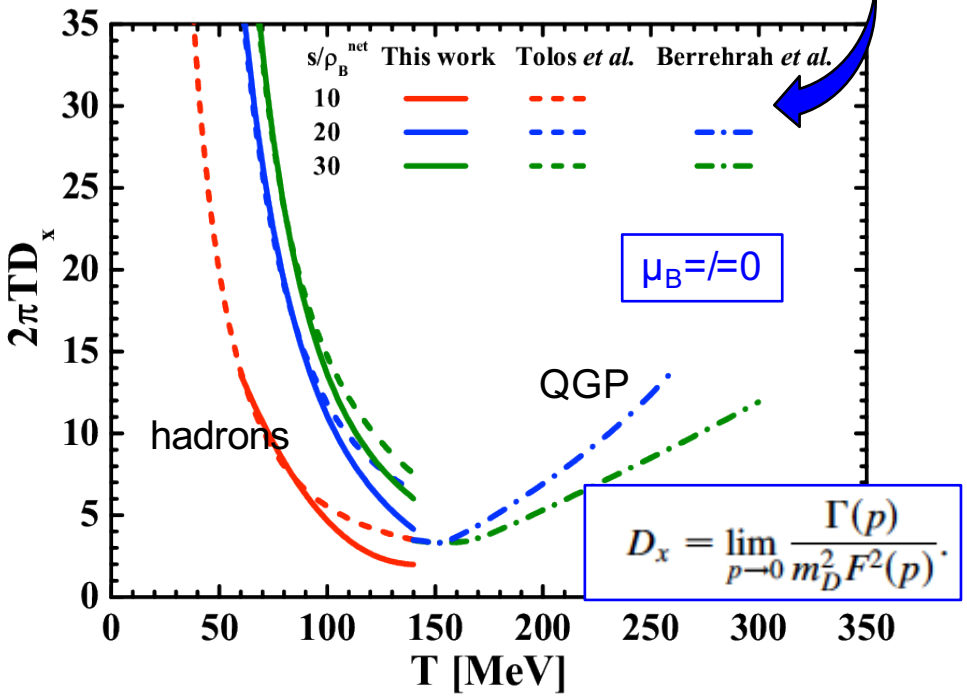


FAIR energies
5-40 AGeV





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

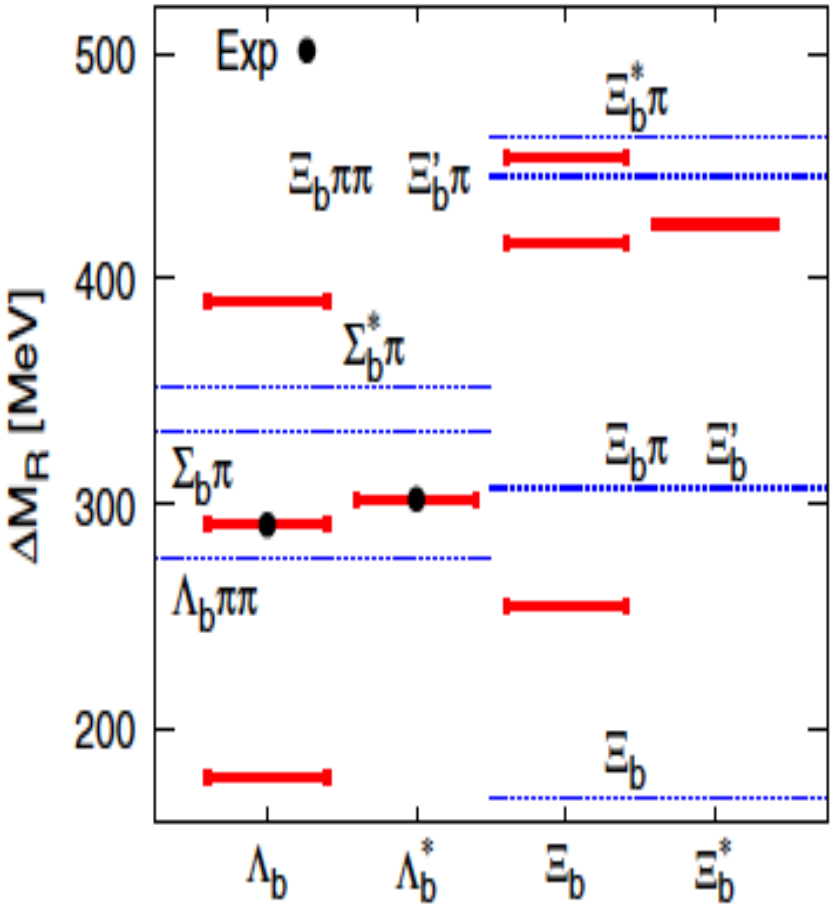


Continuous matching at T_c

Berrehrah et al '14; Ozvenchuk et al '14; Song et al '15

Beauty in Matter

Spectroscopy of excited beauty baryons



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

$\Lambda_b(5912)$ and $\Lambda^*_b(5920)$ found by LHCb* are described as meson-baryon molecular states belonging to a HQSS doublet. In the same SU(3) x HQSS new HQSS partners are predicted: $\Xi_b(6035)$ and $\Xi_b(6043)$

* Aaij et al (LHCb) '12

Recently a Ξ_b* state has been found by LHCb+ in $\Lambda_b K^-$ and $\Xi_b\pi^-$ with

$m_{\Xi b^*}=6226.9\pm2\pm0.3\pm0.2$ MeV

$\Gamma_{\Xi b^*}=18.1\pm5.4\pm1.8$ MeV

+ Aaij et al (LHCb) '18

Our Ξ_b states have lower mass…

work in progress!

Pavao, Nieves and LT, in preparation

Beauty propagation in dense hot matter

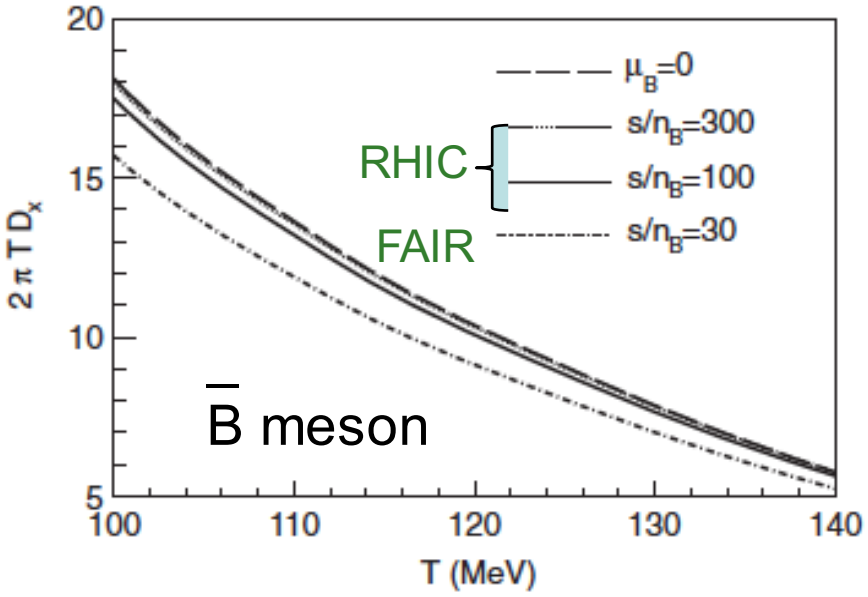
Fokker-Planck equation

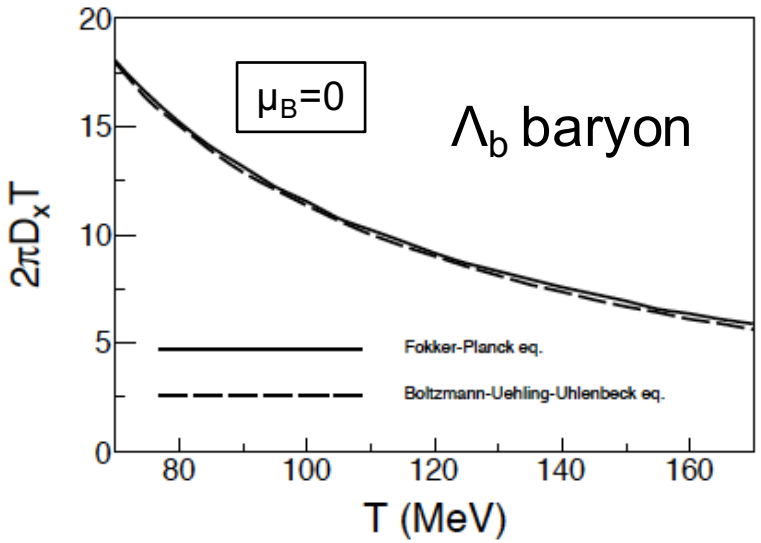
$$\frac{\partial f(t,\mathbf{p})}{\partial t} = \frac{\partial}{\partial p_i}\left\{F_i(\mathbf{p}) f(t,\mathbf{p}) + \frac{\partial}{\partial p_j}\left[\Gamma_{ij}(\mathbf{p}) f(t,\mathbf{p})\right]\right\},$$

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 '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,..)

THOR
CRC-TR 211 Strong-interaction matter under extreme conditions
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