# Heavy Flavor in Nuclear Collisions

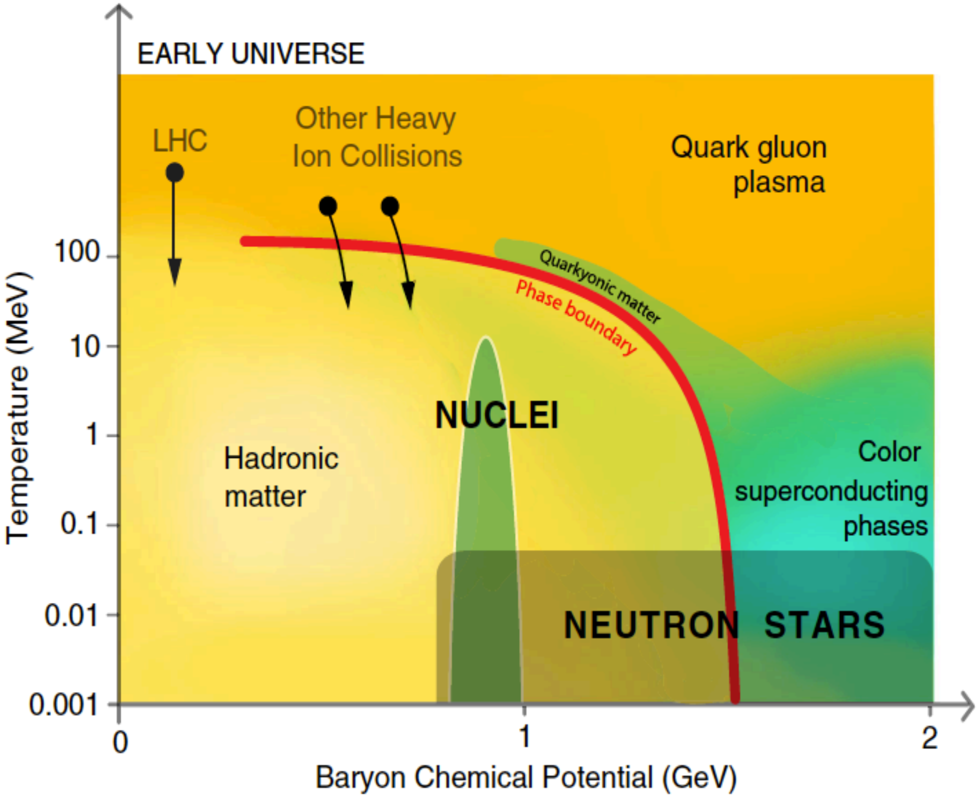
GOETHE UNIVERSITÄT FRANKFURT AM MAIN

**Laura Tolós**

Institute of Space Sciences
CSIC IEEC

2nd EMMI Workshop: Anti-matter, hyper-matter and exotica production at the LHC
6-10 November 2017, Turin (Italy)

# What happens to heavy hadrons at nonzero temperature and density?



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

$\Delta E_{beam}$

**Pion**

**Kaon**

**D-meson**

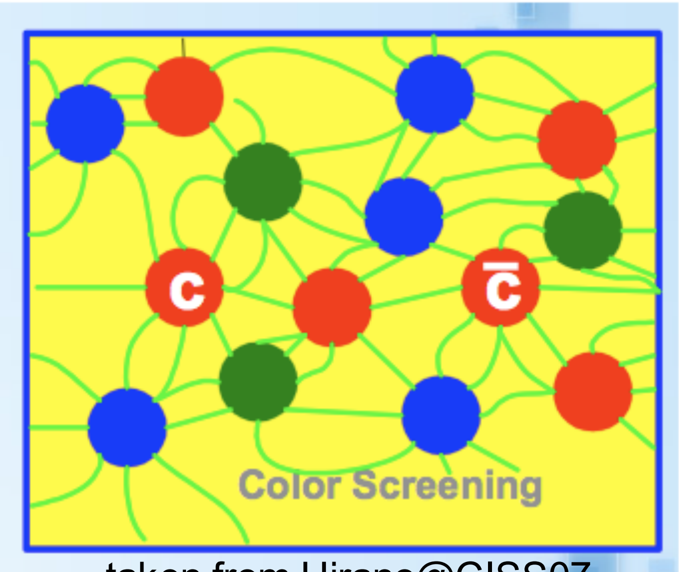
**B-meson**

in this talk !!

# Charm under Extreme Conditions

## $J/\Psi$ suppression

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



taken from Hirano@CISS07

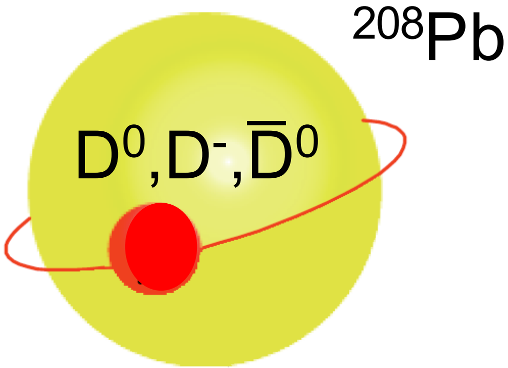
but also comover scattering

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

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

## D-mesic nuclei

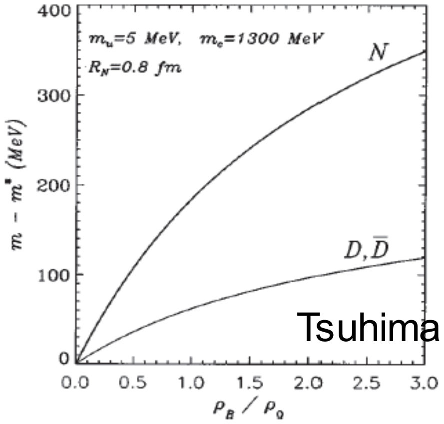
Tsushima et al ’99,
Garcia-Recio et al ’10
Garcia-Recio et al ’12
Yasui et al ’12,
Yamagata-Sekihara ‘16..



# Theoretical models in matter

## QMC model

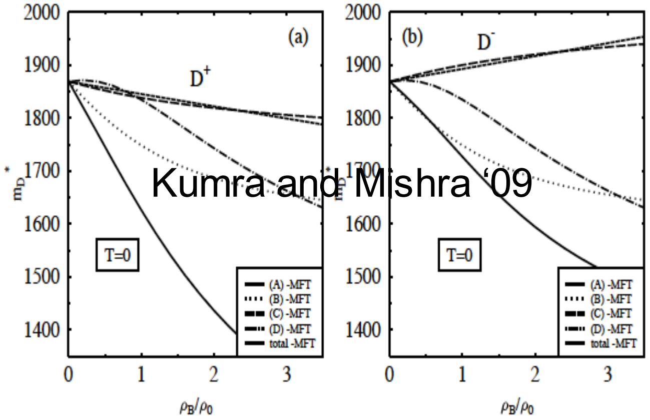
exchange of ω, ρ, σ mesons among quarks in hadron bag



Tsuhima et al '98

Tsushima, Thomas, Krein, Sibirtsev, Fountoura..

## MF/RHF model



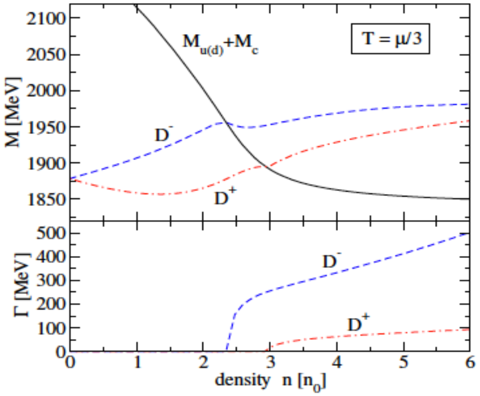
Kumra and Mishra '09

MF/RHF approach that includes charmed mesons

Mazumdar, Mishra, Kumar,..

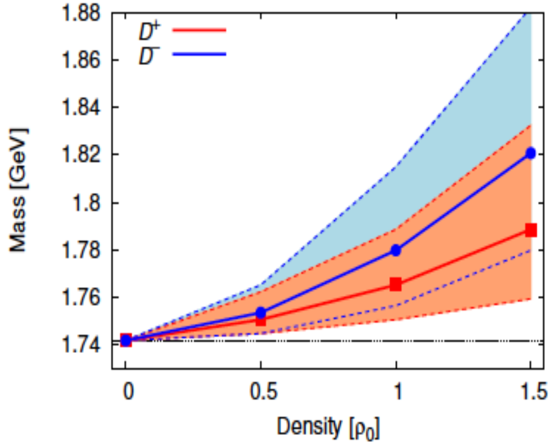
## NJL model

SU(4) NJL model with Polyakov loop



Blaschke, Costa and Kalinovsky '12

## QCD sum-rule

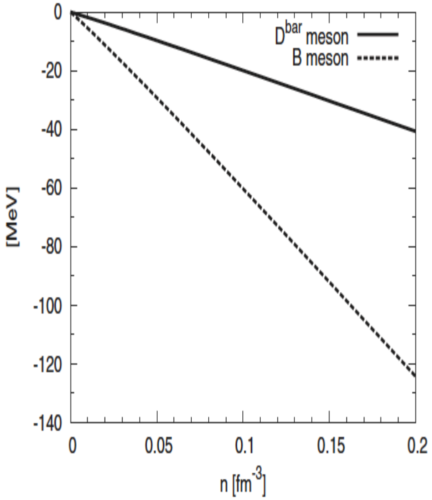


Suzuki, Gubler and Oka '15

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

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

## π exchange with HQ

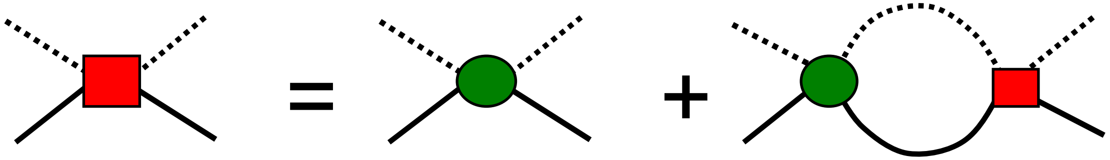


heavy meson - nucleon interaction mediated by π exchange with HQ

Yasui and Sudoh '13

# **Unitarized theory in matter**:
## selfconsistent coupled-channel procedure

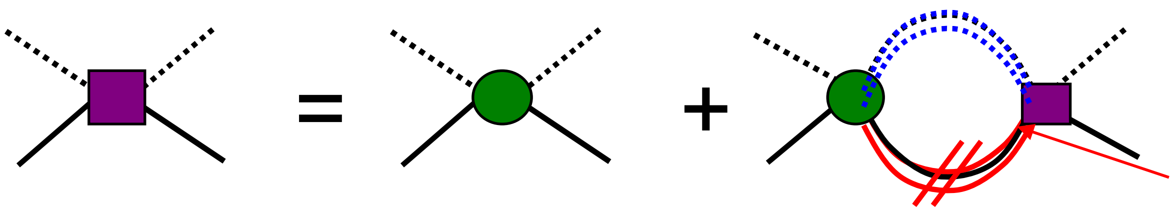
**Free space**



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

meson dressing

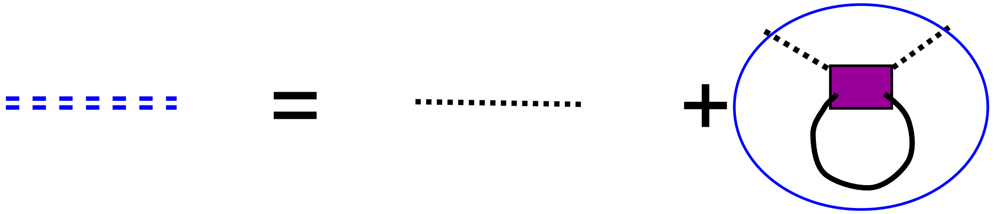
**Medium**



Pauli blocking
and
baryon dressing

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

**Dressed meson:**



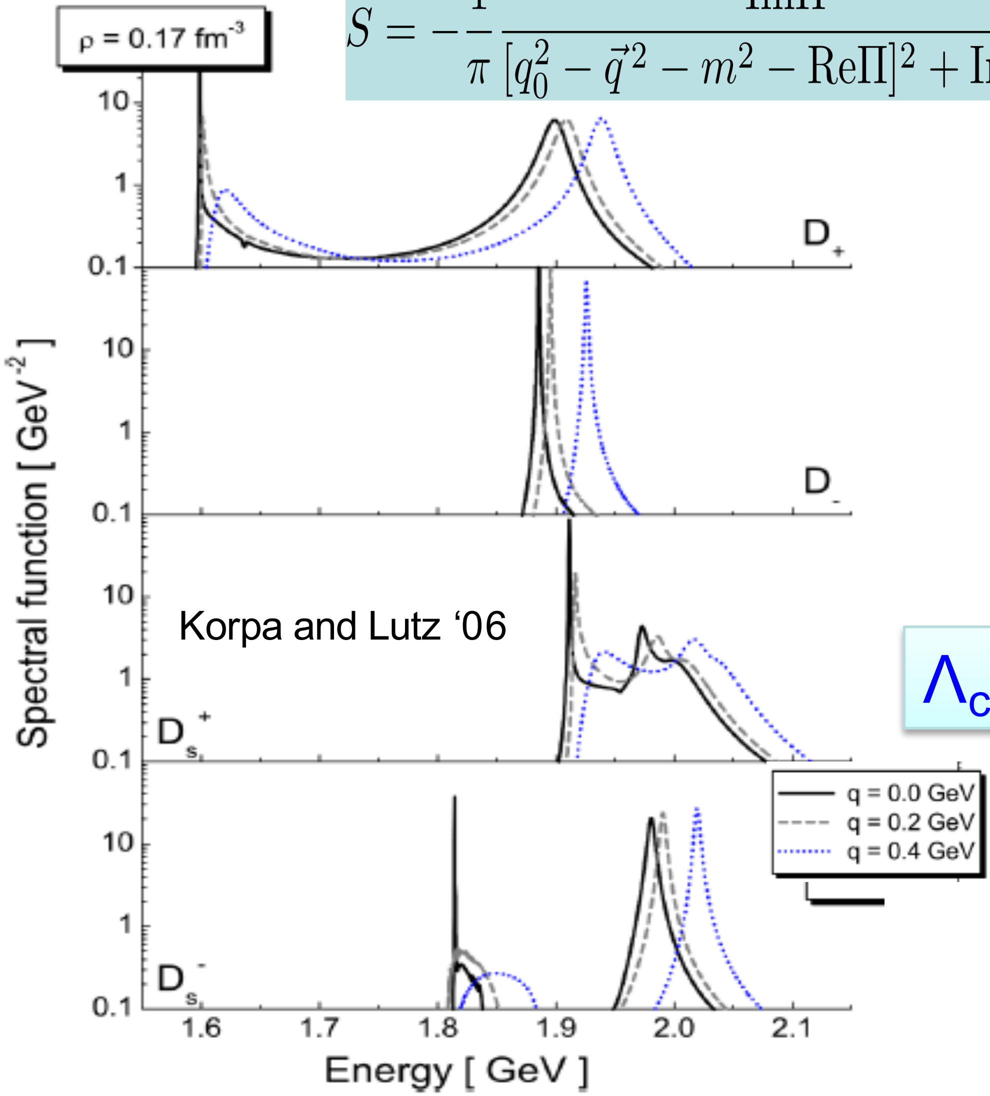
**Π self-energy**

# Unitarized theory in matter

selfconsistent coupled-channel procedure

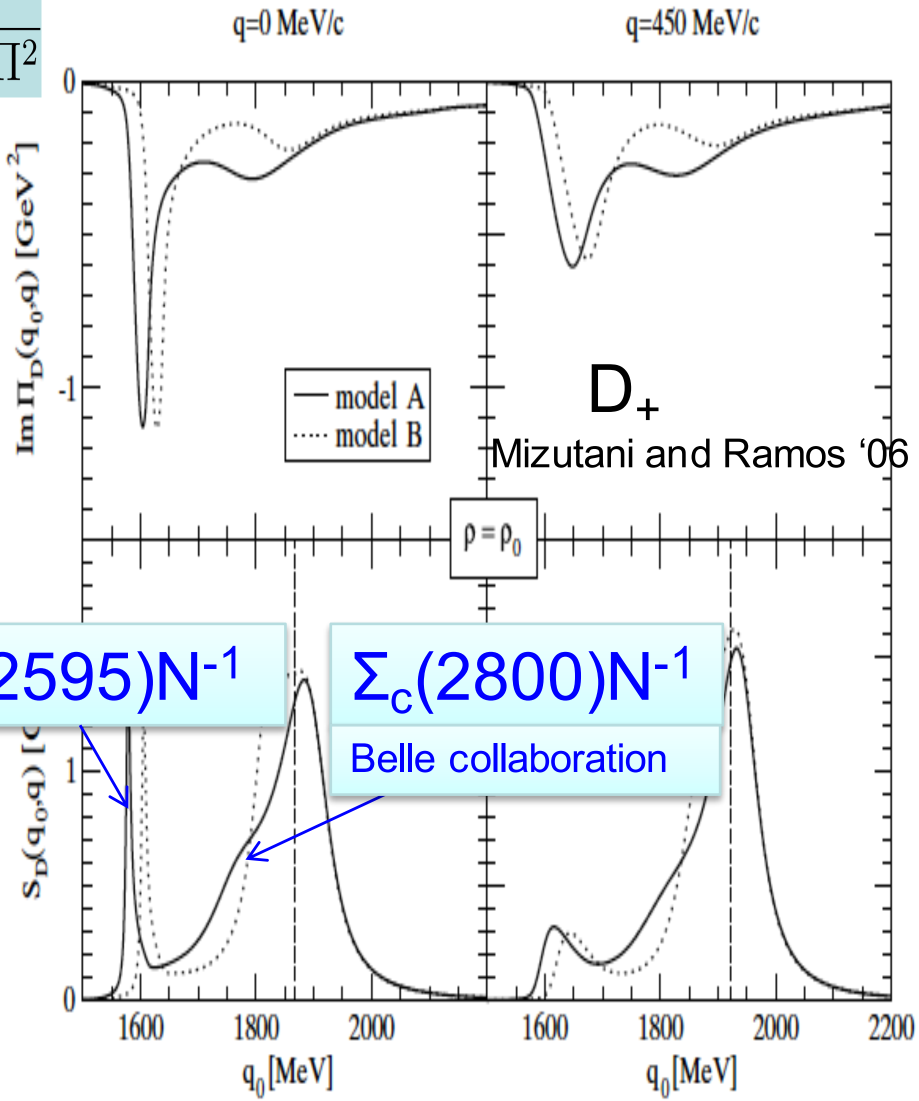
(bare interaction saturated by t-channel vector-meson exchange)

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



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

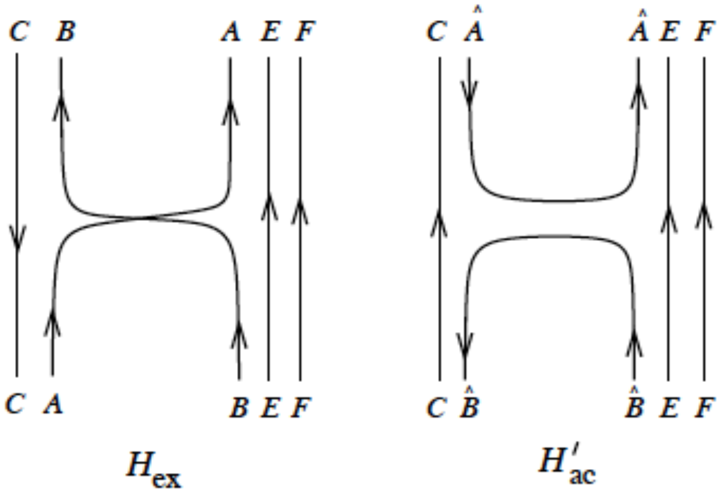
HQSS*: spin interactions vanish for infinitely massive quarks

*Isgur, Wise, Manohar, Neubert

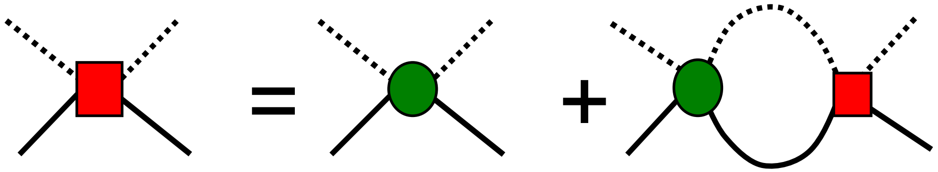
To construct a model for four flavors for pseudoscalar and vector mesons as well as $1/2^+$ and $3/2^+$ baryons that incorporates HQSS in the charm sector: extended WT interaction that fulfills SU(6)xHQSS and it is consistent with chiral symmetry in the light sector

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

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

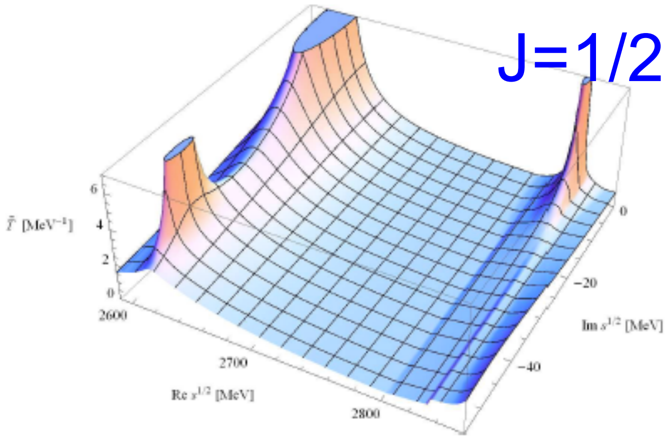
$\Lambda_c$ : C=1,S=0,I=0

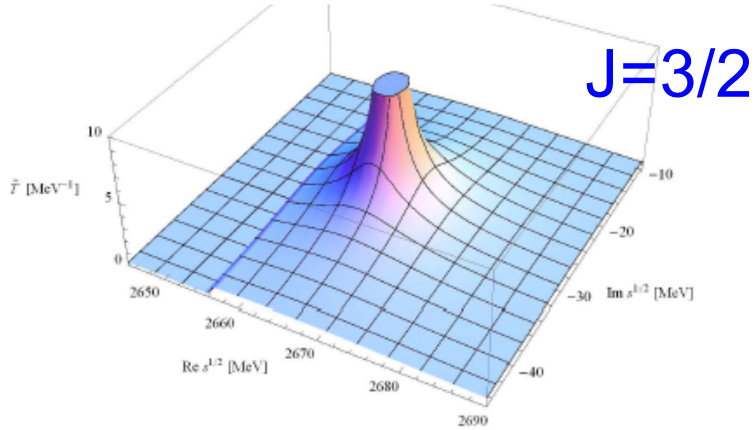
Garcia-Recio et al.’09;
Romanets et al. ’12

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

coupling constant

mass and width



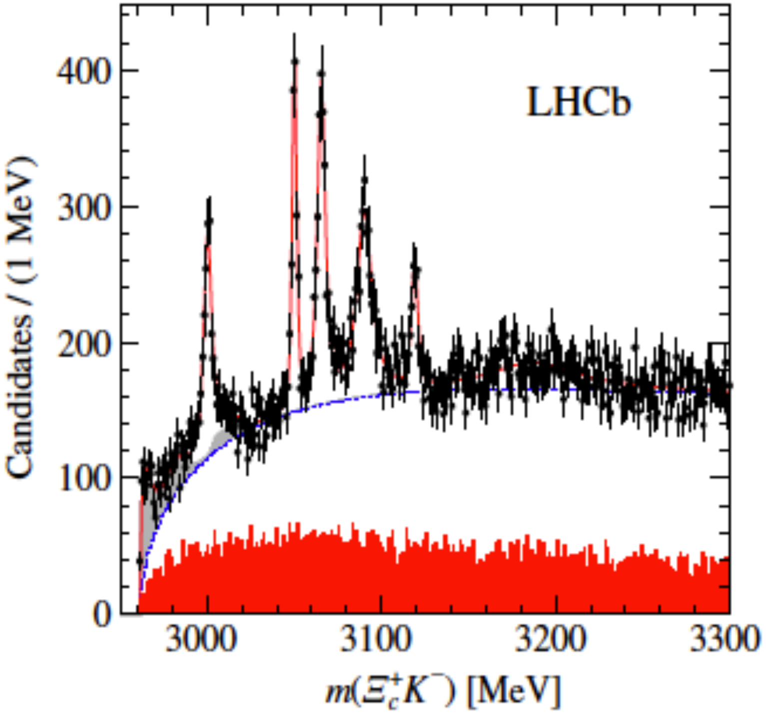


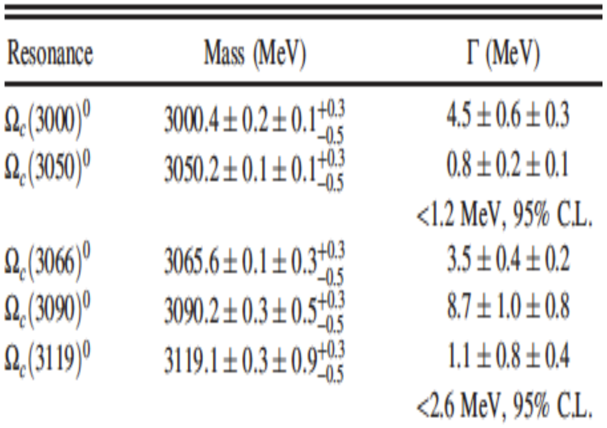
| SU(8) irrep | SU(6) irrep | SU(3) irrep | $M_R$ | $\Gamma_R$ | Couplings to main channels | Status PDG | $J$ |
|---|---|---|---|---|---|---|---|
| **168** | $\mathbf{15}_{2,1}$ | $\mathbf{3}^*_2$ | 2617.3 | 89.8 | $g_{\Sigma_c\pi} = \mathbf{2.3}$, $g_{ND} = 1.6$, $g_{ND^*} = 1.4$, $g_{\Sigma_c\rho} = 1.3$ | | 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 $\Lambda_c(2625)$

# $\Omega_c$ : C=1,S=-2,I=0

Aaij et al (LHCb) ‘17

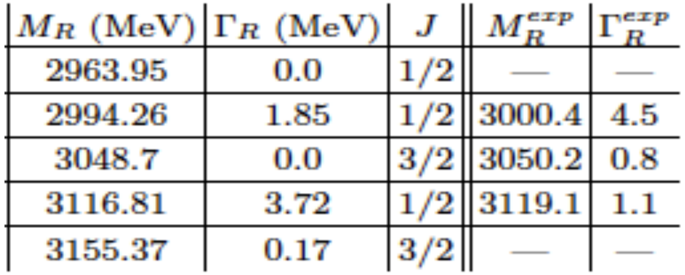




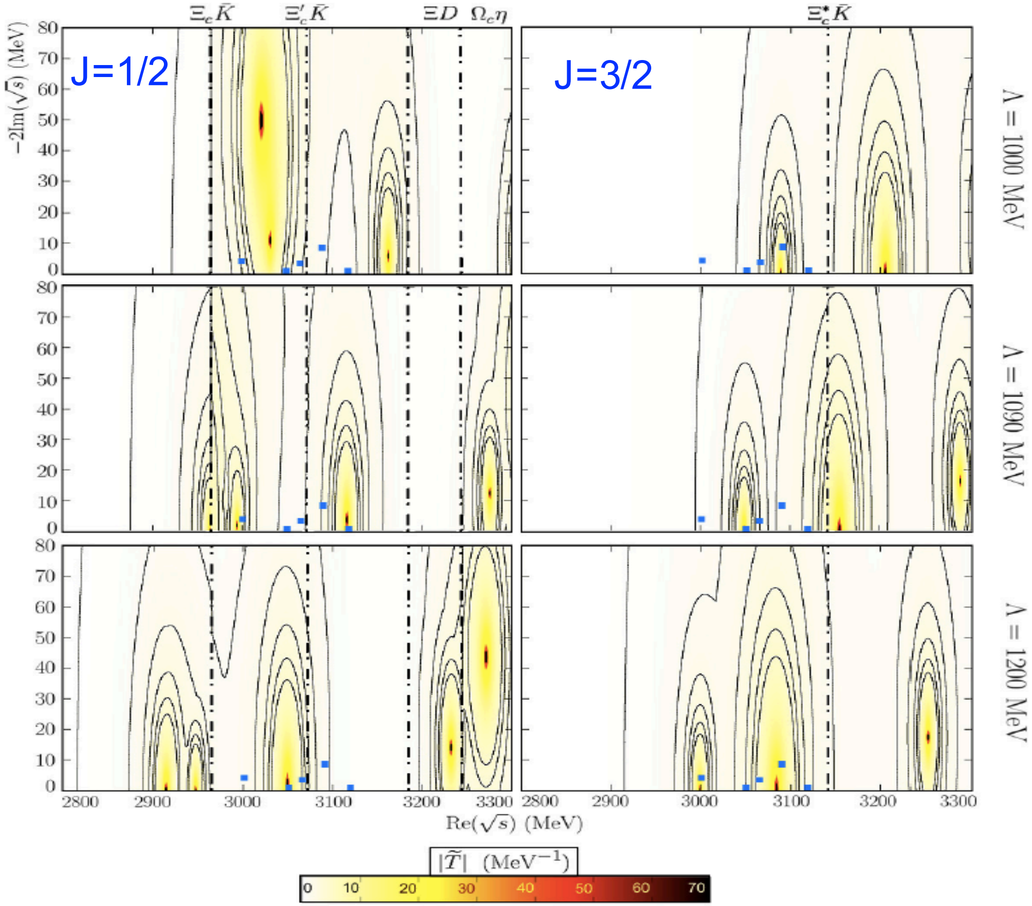
| Resonance | Mass (MeV) | Γ (MeV) |
|---|---|---|
| $\Omega_c(3000)^0$ | $3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$ | $4.5 \pm 0.6 \pm 0.3$ |
| $\Omega_c(3050)^0$ | $3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$ | $0.8 \pm 0.2 \pm 0.1$ |
| | | <1.2 MeV, 95% C.L. |
| $\Omega_c(3066)^0$ | $3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$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

# fine-tuning the subtraction constants (associated to a cutoff)

$\Lambda$=1090 MeV



| $M_R$ (MeV) | $\Gamma_R$ (MeV) | $J$ | $M_R^{exp}$ | $\Gamma_R^{exp}$ |
|---|---|---|---|---|
| 2963.95 | 0.0 | 1/2 | — | — |
| 2994.26 | 1.85 | 1/2 | 3000.4 | 4.5 |
| 3048.7 | 0.0 | 3/2 | 3050.2 | 0.8 |
| 3116.81 | 3.72 | 1/2 | 3119.1 | 1.1 |
| 3155.37 | 0.17 | 3/2 | — | — |

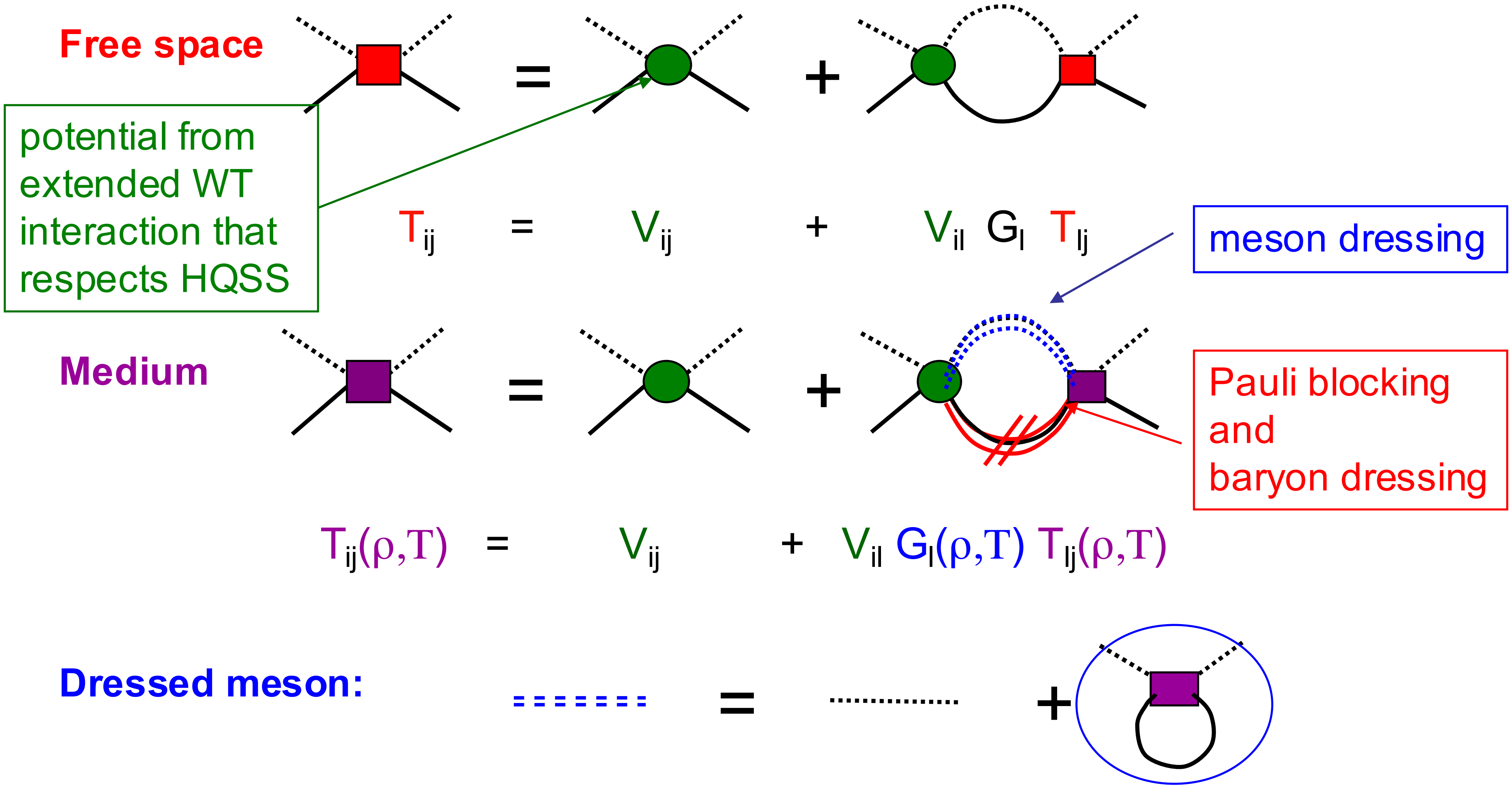


Nieves, Pavao and LT, in preparation

# Charmed hadrons in matter

## Unitarized theory in matter:

selfconsistent coupled-channel procedure



**Free space**

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

potential from extended WT interaction that respects HQSS

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**

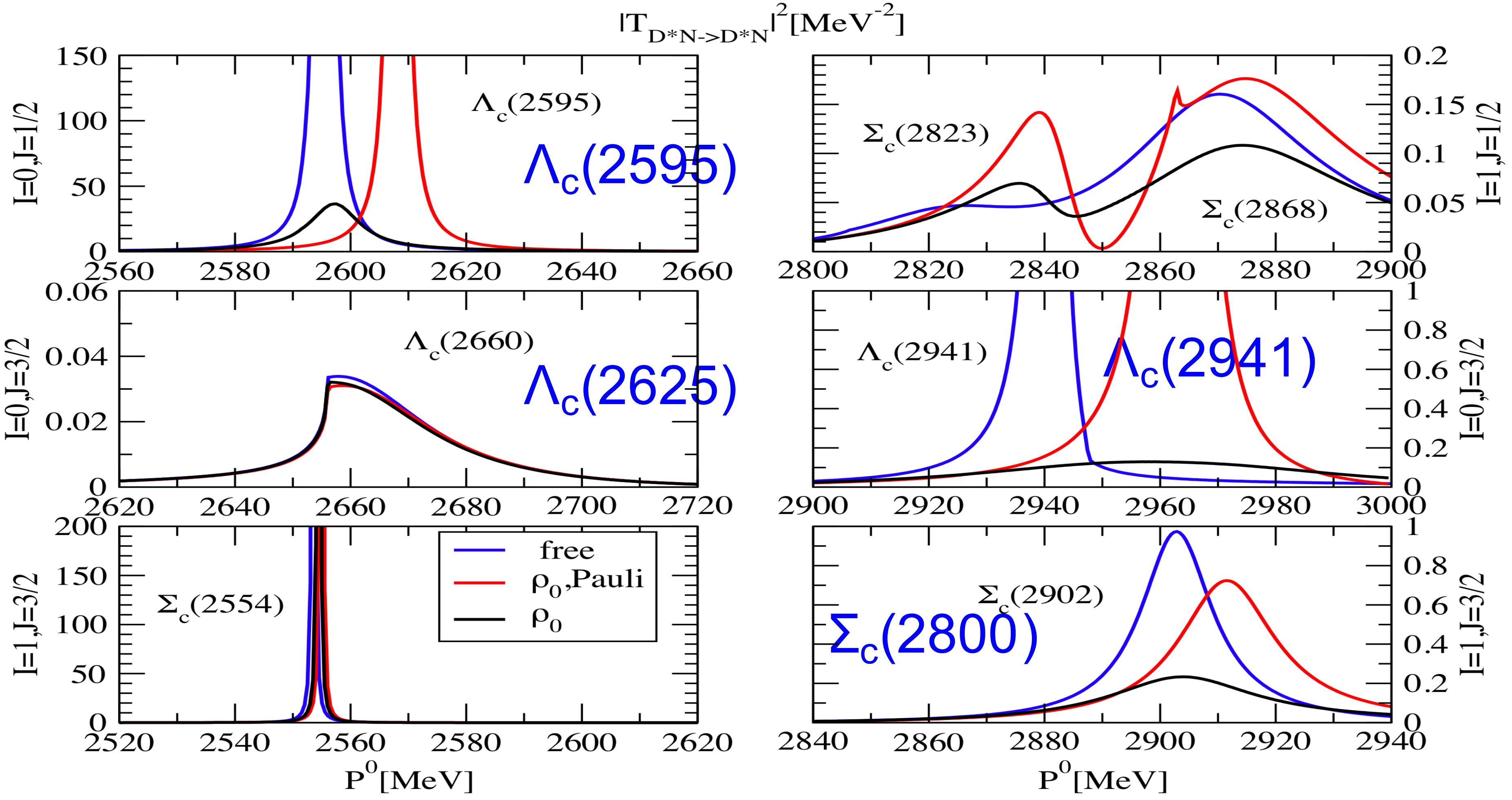
PDG

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

# 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]



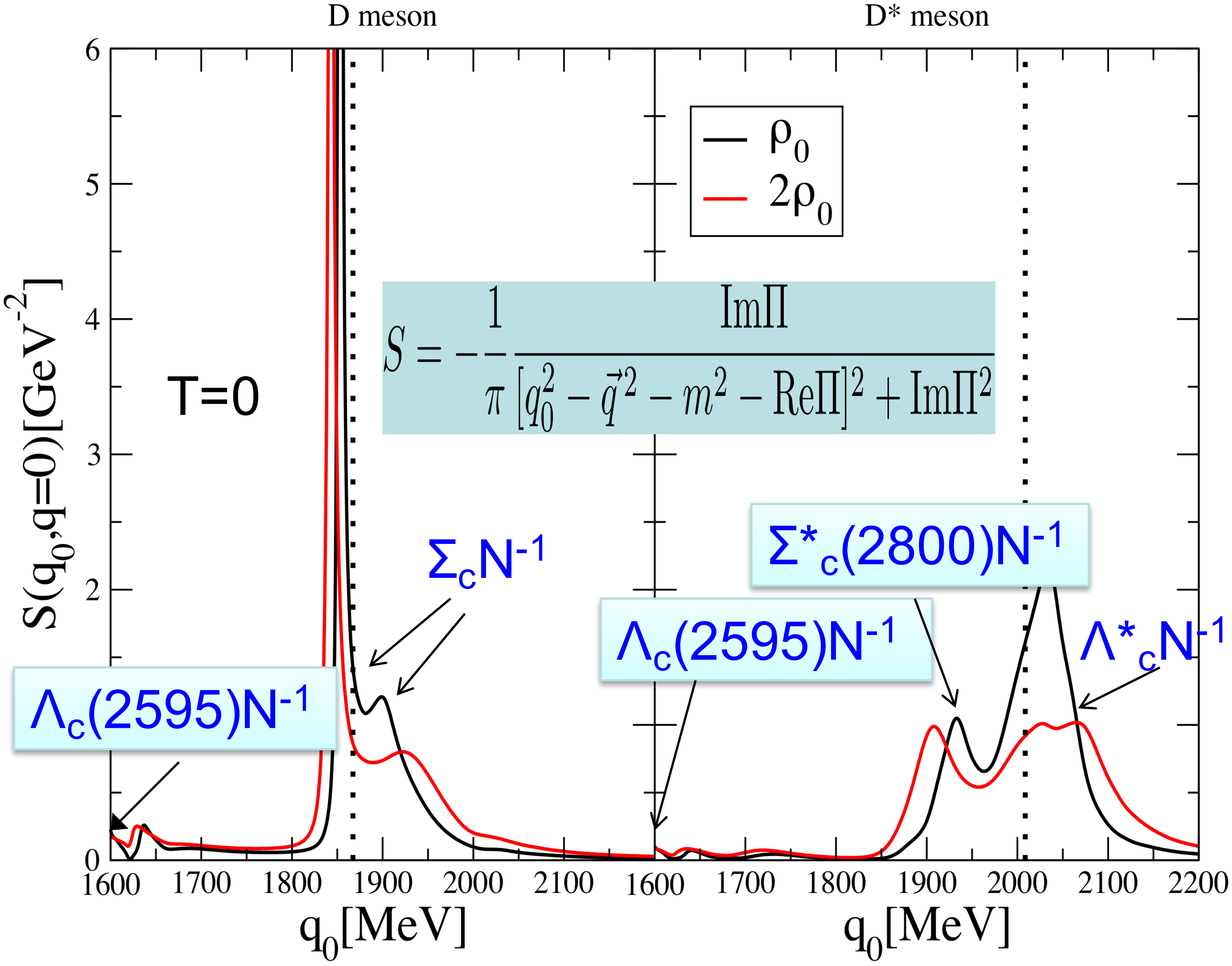
$\Lambda_c(2595)$

$\Lambda_c(2625)$

$\Lambda_c(2941)$

$\Sigma_c(2800)$

# 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

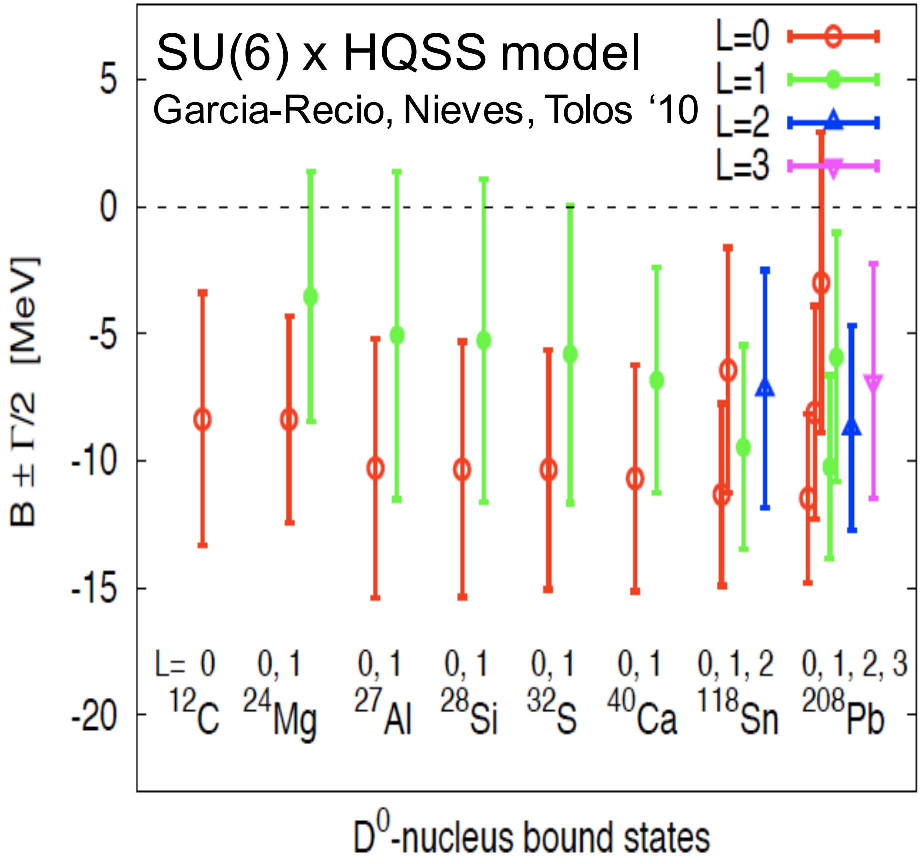
Garcia-Recio et al ’09
LT et al. ‘10;
Gamermann et al. ‘10
Garcia-Recio et al. ‘10
Garcia-Recio et al.’12
Romanets et al. ’12
Garcia-Recio et al.(1) ‘13
Garcia-Recio et al.(2) ‘13

# D-mesic nuclei

Solving Schroedinger or Klein-Gordon equation with

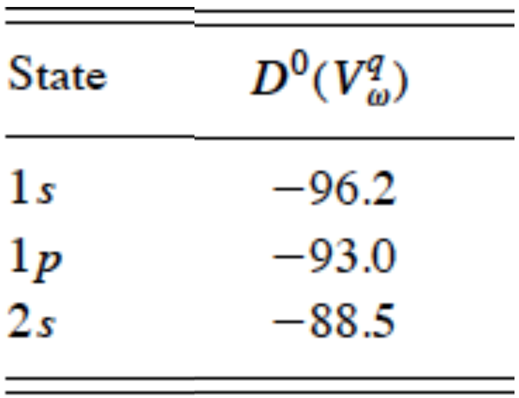
- potential from QMC model
- potential from SU(6) x HQSS model
- potential from π exchange model with HQS

$D^0$ and $D^+$



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

$^{208}$Pb



| State | $D^0(V^q_\omega)$ |
|---|---|
| $1s$ | $-96.2$ |
| $1p$ | $-93.0$ |
| $2s$ | $-88.5$ |

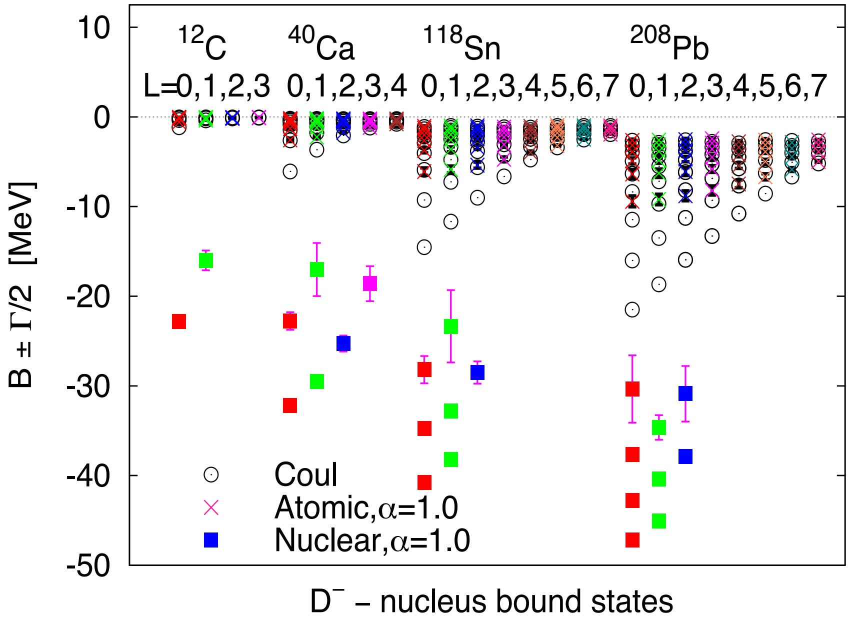
Tsushima et al. '99
Krein et al '17 (review)

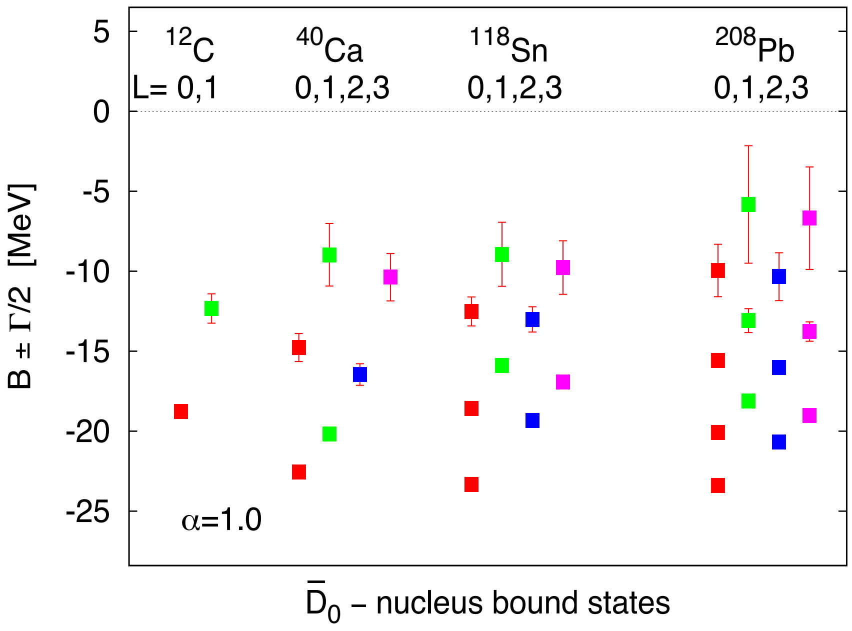
- SU(6) x HQSS model:
$D^+$ does not bind

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

## SU(6) x HQSS model:

Garcia-Recio, Nieves, Salcedo and Tolos '12

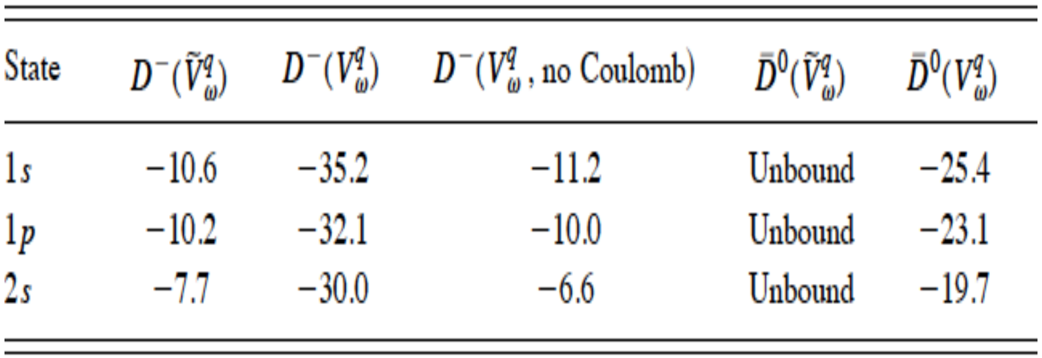




## QMC model

Tsushima, Lu,Thomas, Saito and Landau ' 99
Krein, Thomas and Tsushima '17 (review)

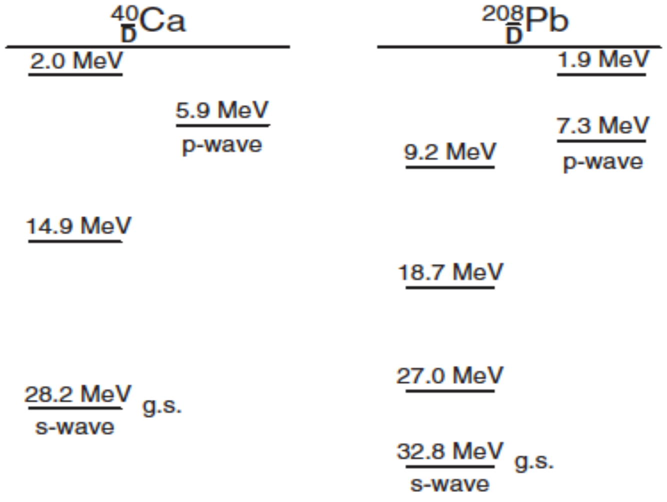
$^{208}$Pb



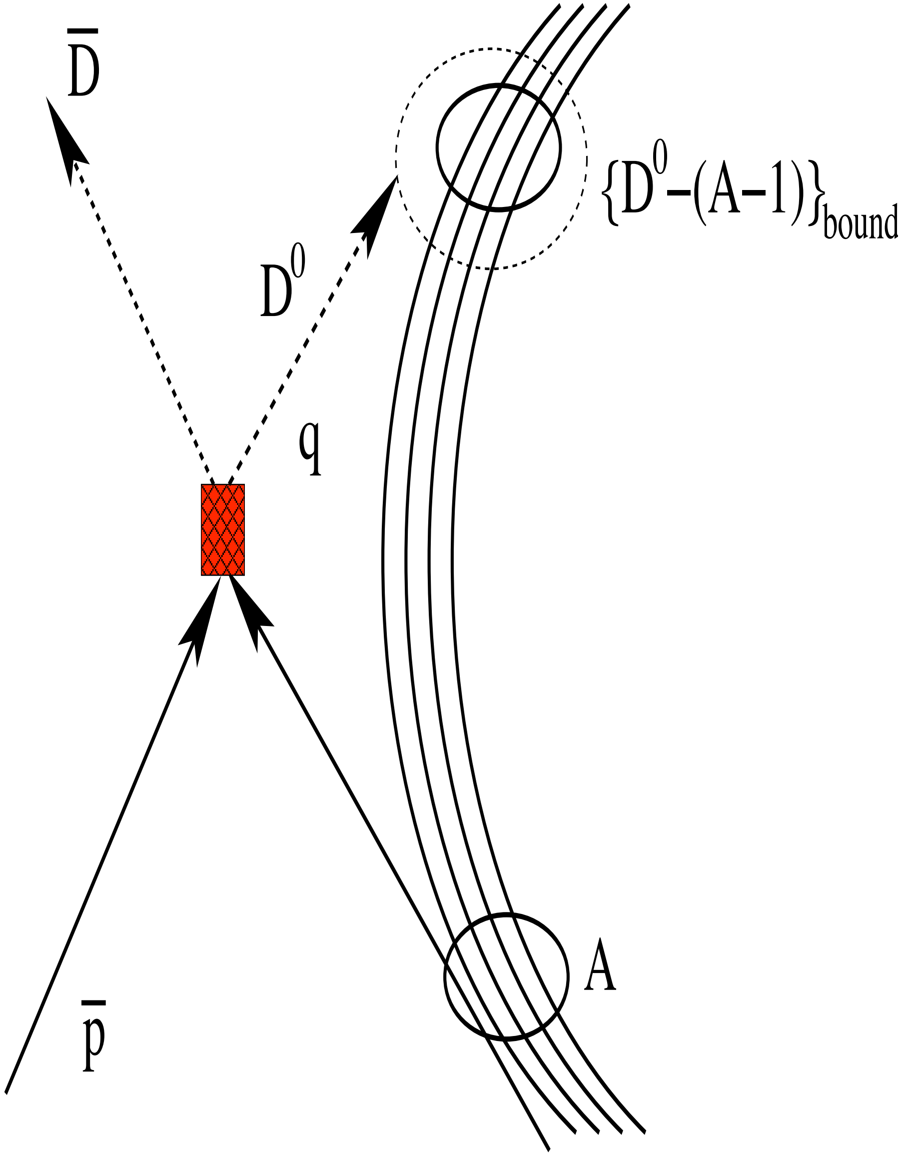
| State | $D^-(\tilde{V}^q_\omega)$ | $D^-(V^q_\omega)$ | $D^-(V^q_\omega$, no Coulomb) | $\bar{D}^0(\tilde{V}^q_\omega)$ | $\bar{D}^0(V^q_\omega)$ |
|---|---|---|---|---|---|
| 1*s* | −10.6 | −35.2 | −11.2 | Unbound | −25.4 |
| 1*p* | −10.2 | −32.1 | −10.0 | Unbound | −23.1 |
| 2*s* | −7.7 | −30.0 |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

## π exchange model with HQS

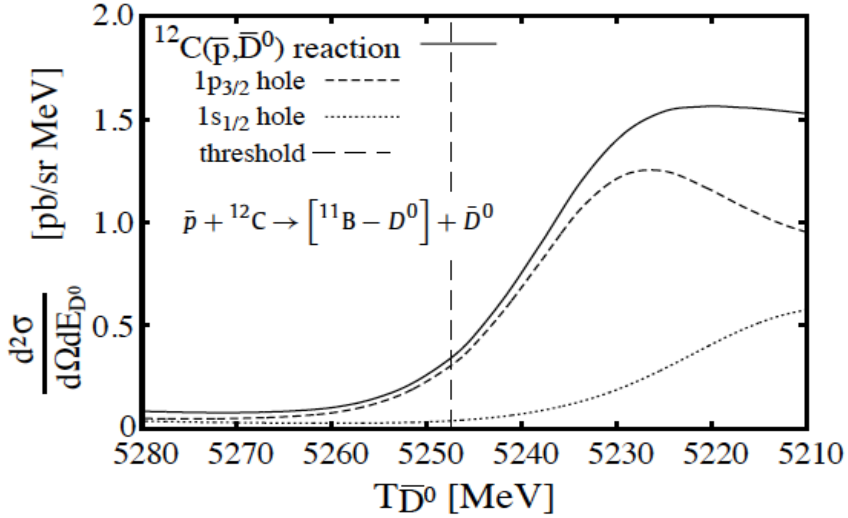
Yasui and Sudoh '13



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



Yamagata-Sekihara, Garcia-Recio, Nieves, Salcedo and Tolos '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

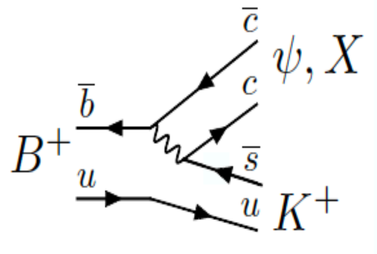
$$\bar{p} + p \to D^{*-} + D^+,$$

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

# Charm resonances in matter: X(3872)

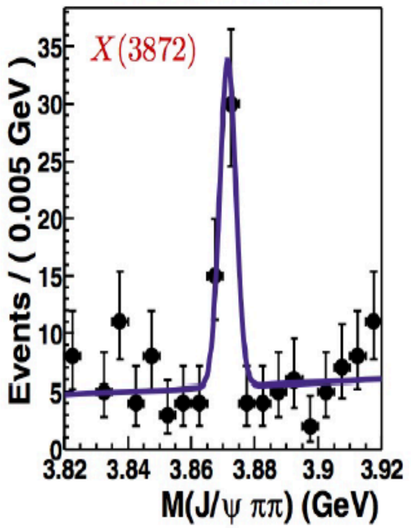
## as D $\bar{\mathrm{D}}$* molecule

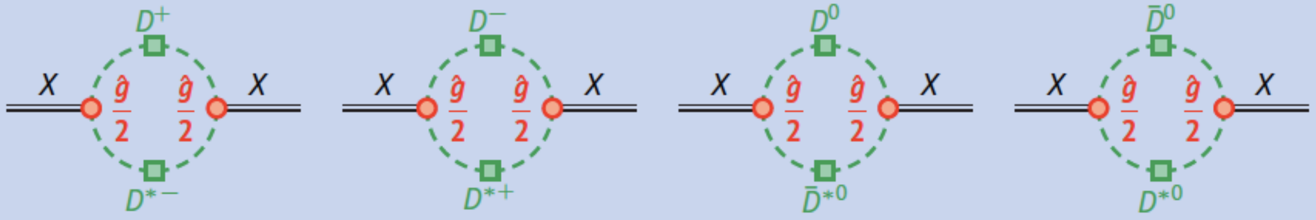
*B decays: Belle, BaBar, LHCb, etc.*

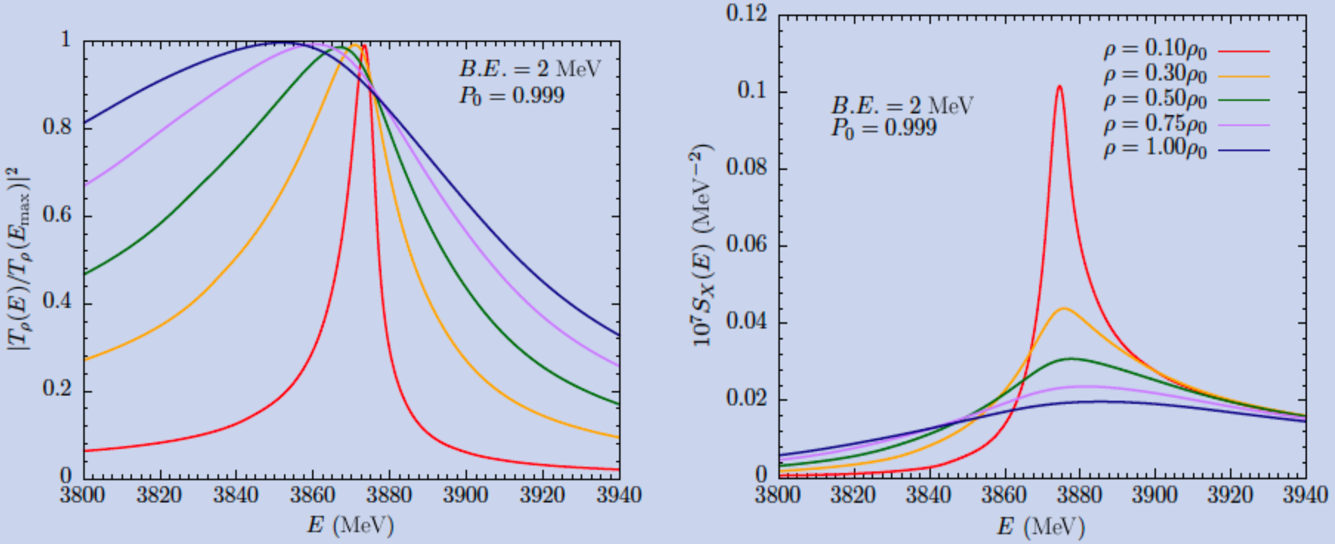


$B \to KX; X \to \pi^+\pi^- J/\psi$ at Belle

PRL91,262001 (2003)







| | $P_0 = 0.999$ | |
|---|---|---|
| $\rho/\rho_0$ | $E_{\max}$ (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 ($m_D >> m_{bath}$, $m_D >> T_{bath}$)

$$\frac{\partial f(t,\mathbf{p})}{\partial t} = \frac{\partial}{\partial p_i}\left\{\overset{\text{drag force}}{\boxed{F_i(\mathbf{p})}} f(t,\mathbf{p}) + \frac{\partial}{\partial p_j}\left[\overset{\text{diffusion coefficient}}{\boxed{\Gamma_{ij}(\mathbf{p})}} f(t,\mathbf{p})\right]\right\},$$

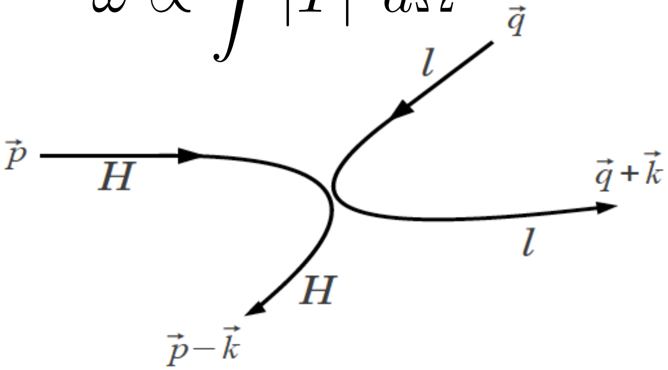
isotropic bath

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

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

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

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



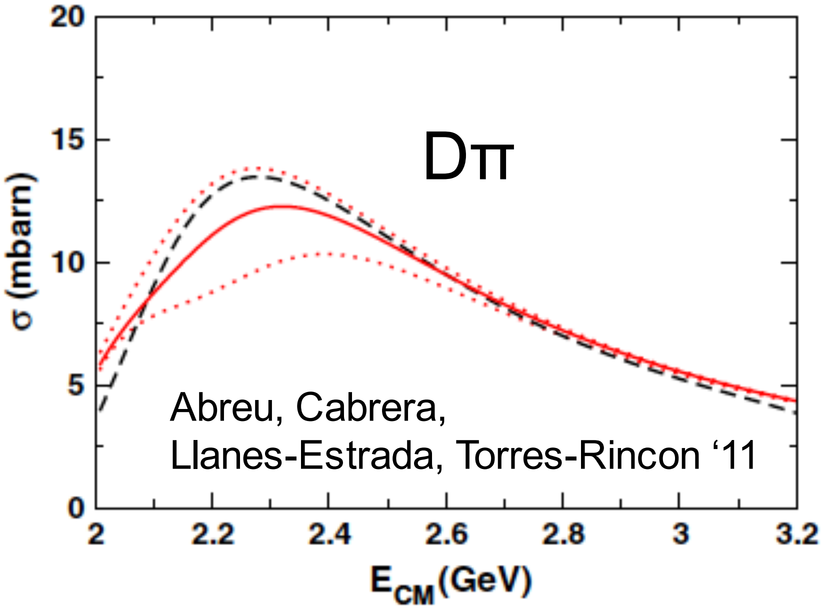
Previous works Laine ‘11; He, Fries, Rapp ‘11; Ghosh, Das, Sarkar, -eAlam ’11

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

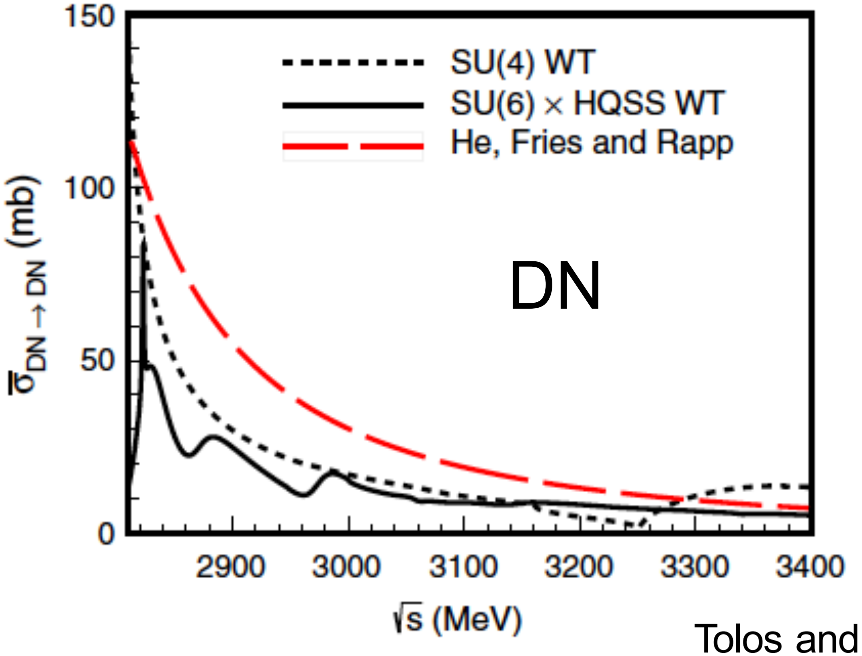
# (Vacuum) cross sections for open charm with mesons and baryons

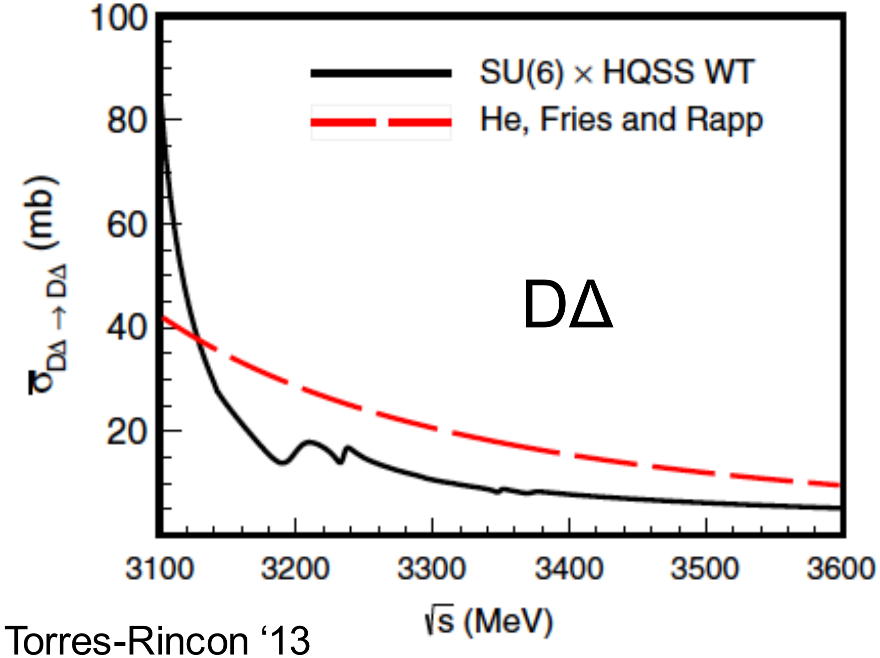
D-mesons with light mesons
(π, K, K, η)



Abreu, Cabrera,
Llanes-Estrada, Torres-Rincon ‘11

D-mesons with baryons (N, Δ)

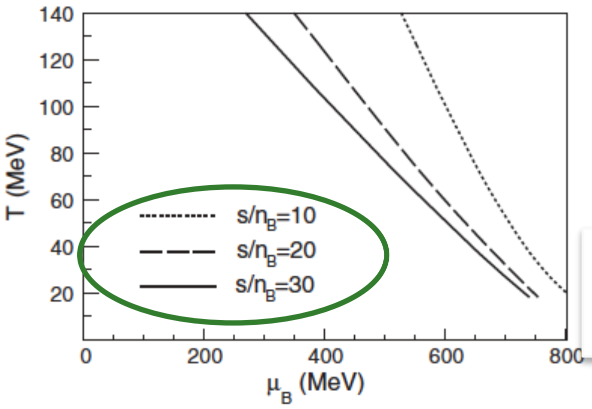




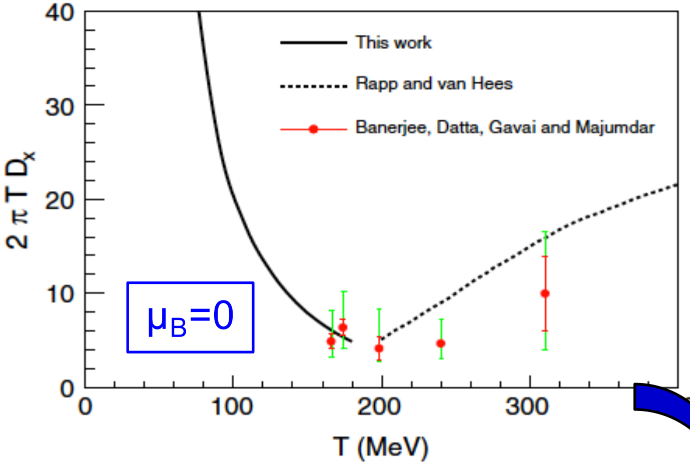
Tolos and Torres-Rincon ‘13

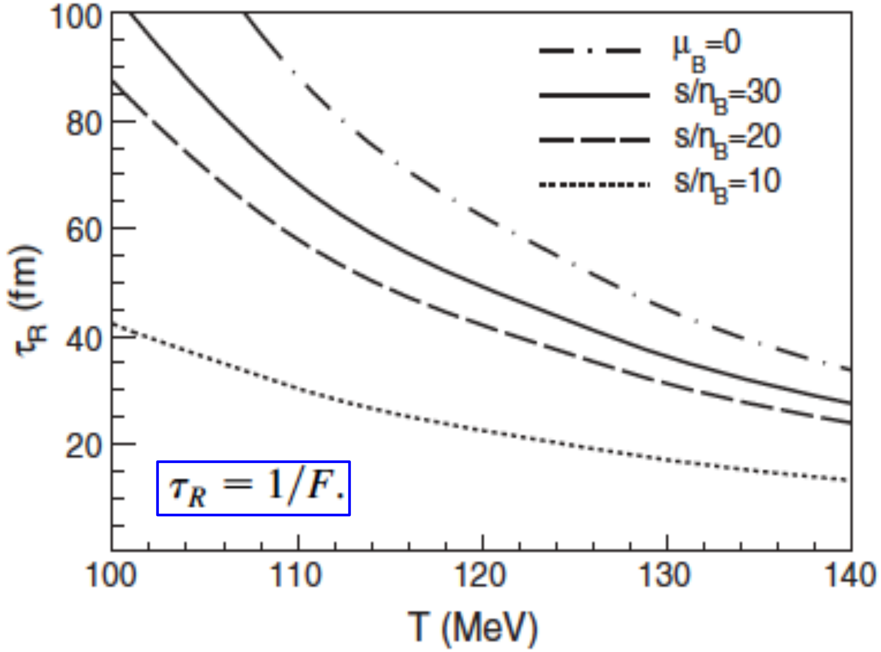
# Some results for CBM@FAIR energies

LT and Torres-Rincon '13



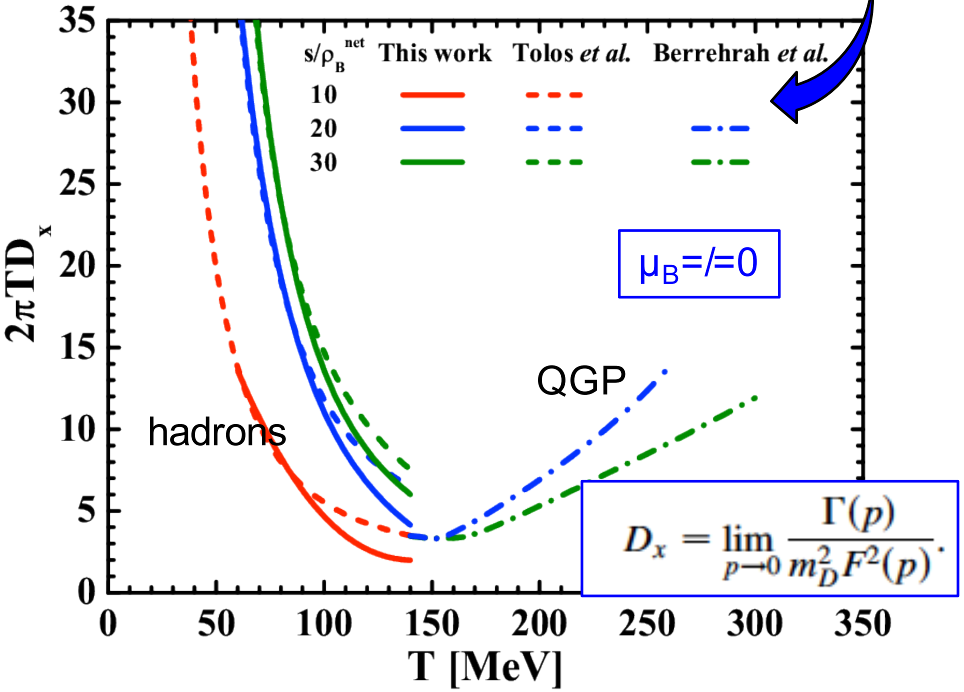
FAIR energies
5-40 AGeV





$$\tau_R = 1/F.$$

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



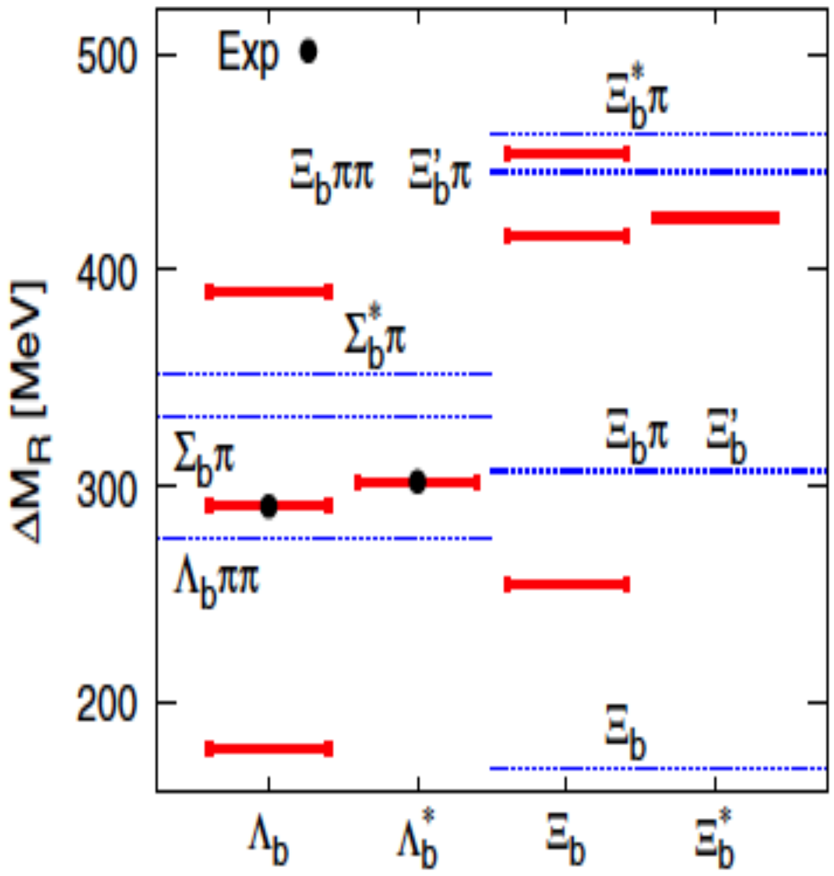
$$D_x = \lim_{p \to 0} \frac{\Gamma(p)}{m_D^2 F^2(p)}.$$

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

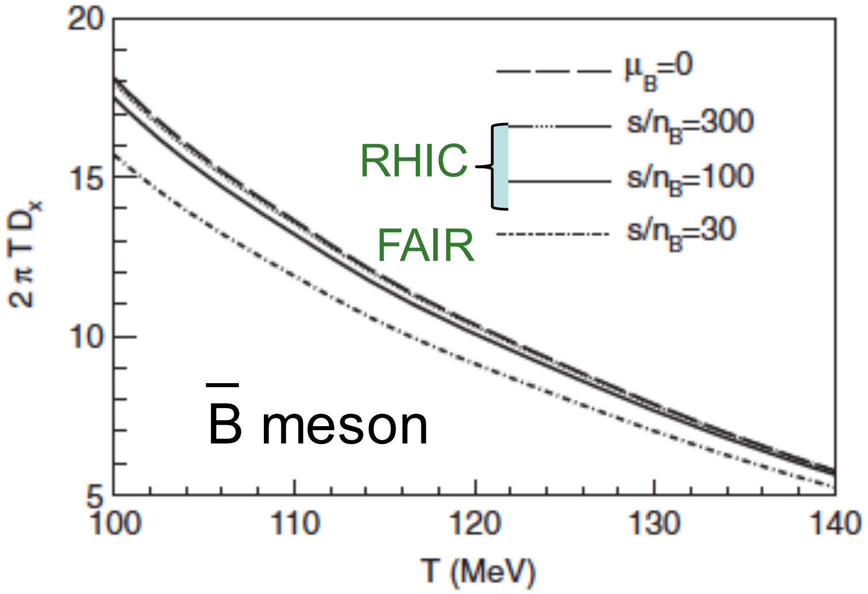
# Beauty propagation in dense hot matter

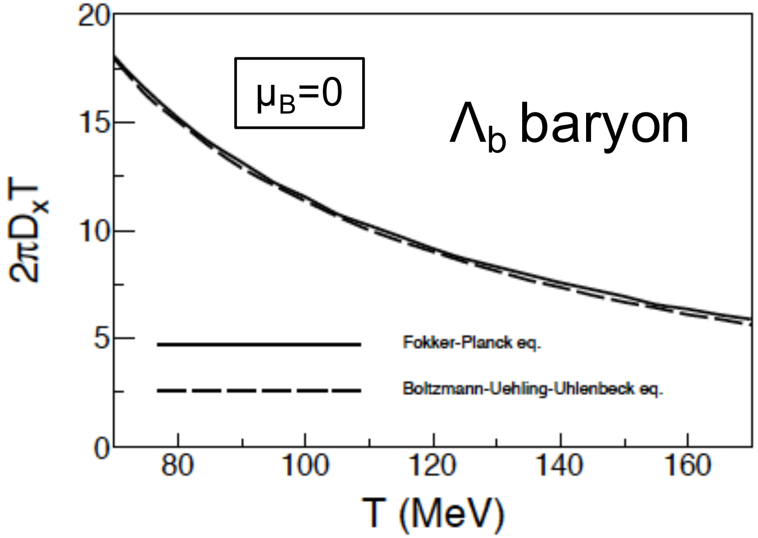
Fokker-Planck equation

$$\frac{\partial f(t,\mathbf{p})}{\partial t} = \frac{\partial}{\partial p_i}\left\{\underset{\text{drag force}}{\boxed{F_i(\mathbf{p})}} f(t,\mathbf{p}) + \frac{\partial}{\partial p_j}\left[\underset{\text{diffusion coefficient}}{\boxed{\Gamma_{ij}(\mathbf{p})}} f(t,\mathbf{p})\right]\right\},$$

Results from FAIR to RHIC energies (LHC?)

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 $\Lambda_b$

# 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

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