JOINT INSTITUTE FOR NUCLEAR RESEARCH

Strangeness in Quark Matter

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# Heavy Hadrons in Dense Matter

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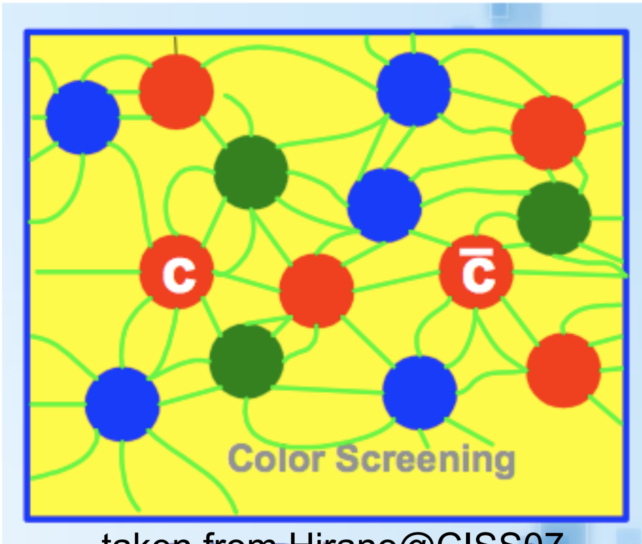
# Charm under Extremes Conditions

## J/Ψ suppression

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




taken from Hirano@CISS07

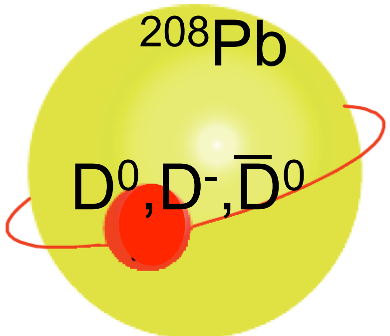
but also comover scattering

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

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

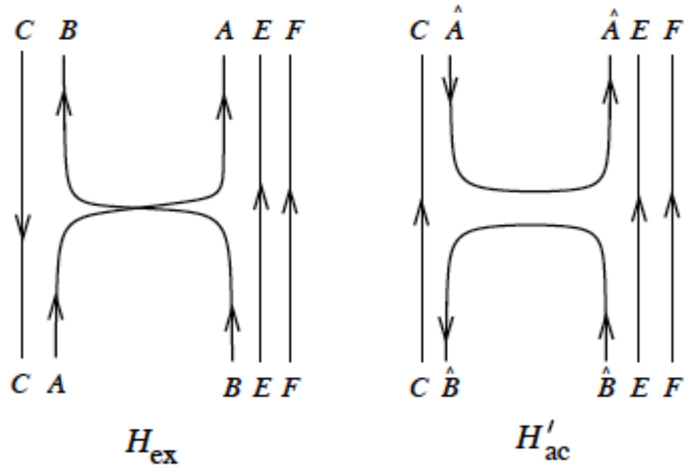
HQSS*: spin interactions vanish for infinitely massive quarks

*Isgur, Wise, Manohar, Neubert

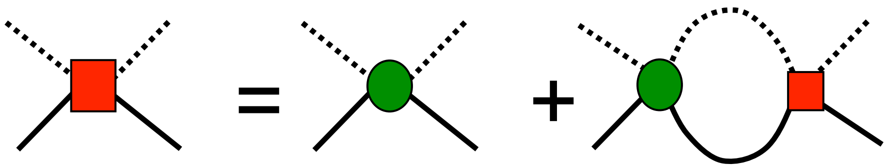
To construct a model for four flavors for pseudoscalar and vector mesons as well as $1/2^+$ and $3/2^+$ baryons that incorporates HQSS in the charm sector: extended WT interaction that fulfills SU(6)xHQSS and it is consistent with chiral symmetry in the light sector

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

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




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



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

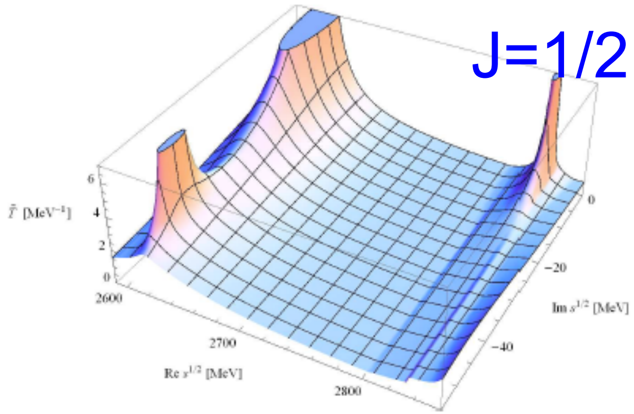
# Spectroscopy of excited charmed baryons

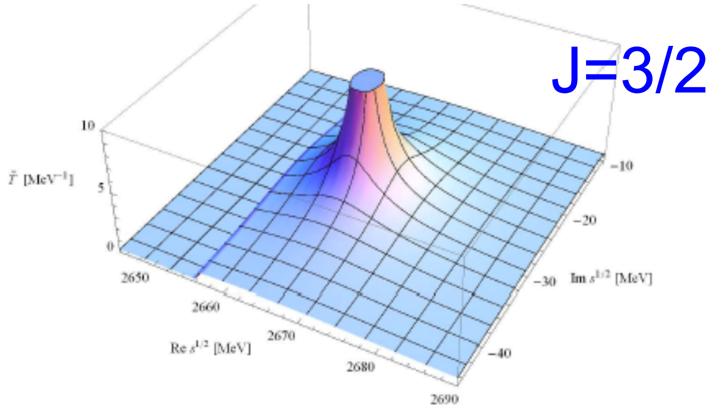
## $\Lambda_c$ : C=1,S=0,I=0

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 ($g_i g_j$); mass and width ($s_R$)




| SU(8) irrep | SU(6) irrep | SU(3) irrep | $M_R$ | $\Gamma_R$ | Couplings to main channels | Status PDG | $J$ |
|---|---|---|---|---|---|---|---|
| 168 | $15_{2,1}$ | $3^*_2$ | 2617.3 | 89.8 | $g_{\Sigma_c\pi}=2.3$, $g_{ND}=1.6$, $g_{ND^*}=1.4$, $g_{\Sigma_c\rho}=1.3$ | | 1/2 |
| 168 | $15_{2,1}$ | $3^*_4$ | 2666.6 | 53.7 | $g_{\Sigma_c^*\pi}=2.2$, $g_{ND^*}=2.0$, $g_{\Sigma_c\rho}=0.8$, $g_{\Sigma_c^*\rho}=1.3$ | $\Lambda_c(2625)$ *** | 3/2 |
| 168 | $21_{2,1}$ | $3^*_2$ | 2618.8 | 1.2 | $g_{\Sigma_c\pi}=0.$[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 | $21_{2,1}$ | $3^*_2$ | 2828.4 | 0.8 | $g_{ND}=0.3$, $g_{\Lambda_c\eta}=1.1$, $g_{\Xi_c K}=1.6$, $g_{\Lambda D_s^*}=1.1$, $g_{\Sigma_c\rho}=1.1$, $g_{\Sigma_c^*\rho}=1.0$, $g_{\Xi_c^* K^*}=0.8$ | | 1/2 |

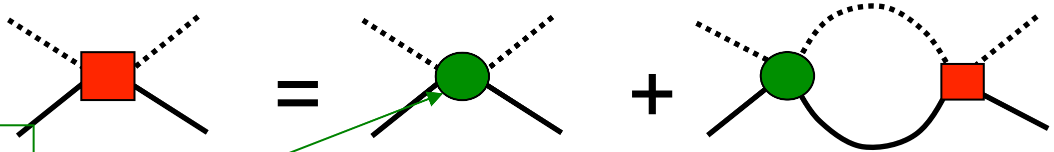
- $\Lambda_c(2595)$ has large DN and D*N components
- Double-pole pattern for $\Lambda_c(2595)$, like for $\Lambda(1405)$
- Identification of $\Lambda_c(2625)$

# Charmed hadrons in matter

## Unitarized theory in matter:

selfconsistent coupled-channel procedure

**Free space**

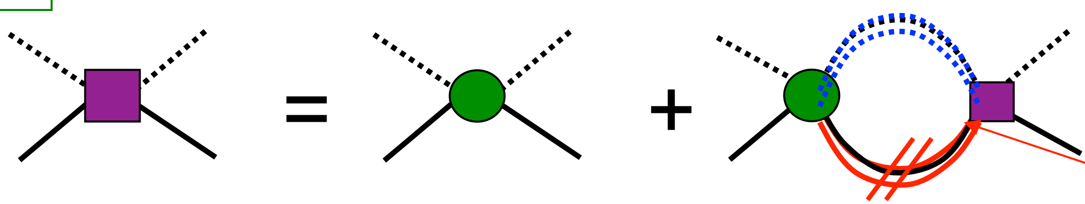


potential from extended WT interaction that respect HQSS

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

meson dressing

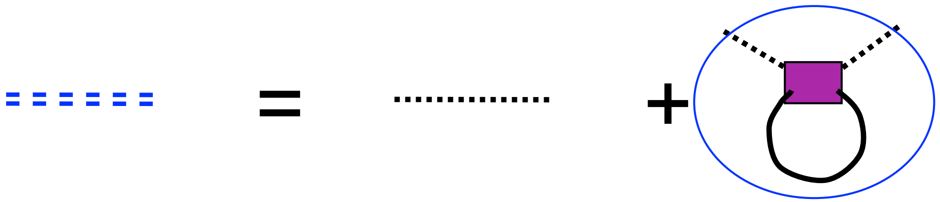
**Medium**



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**

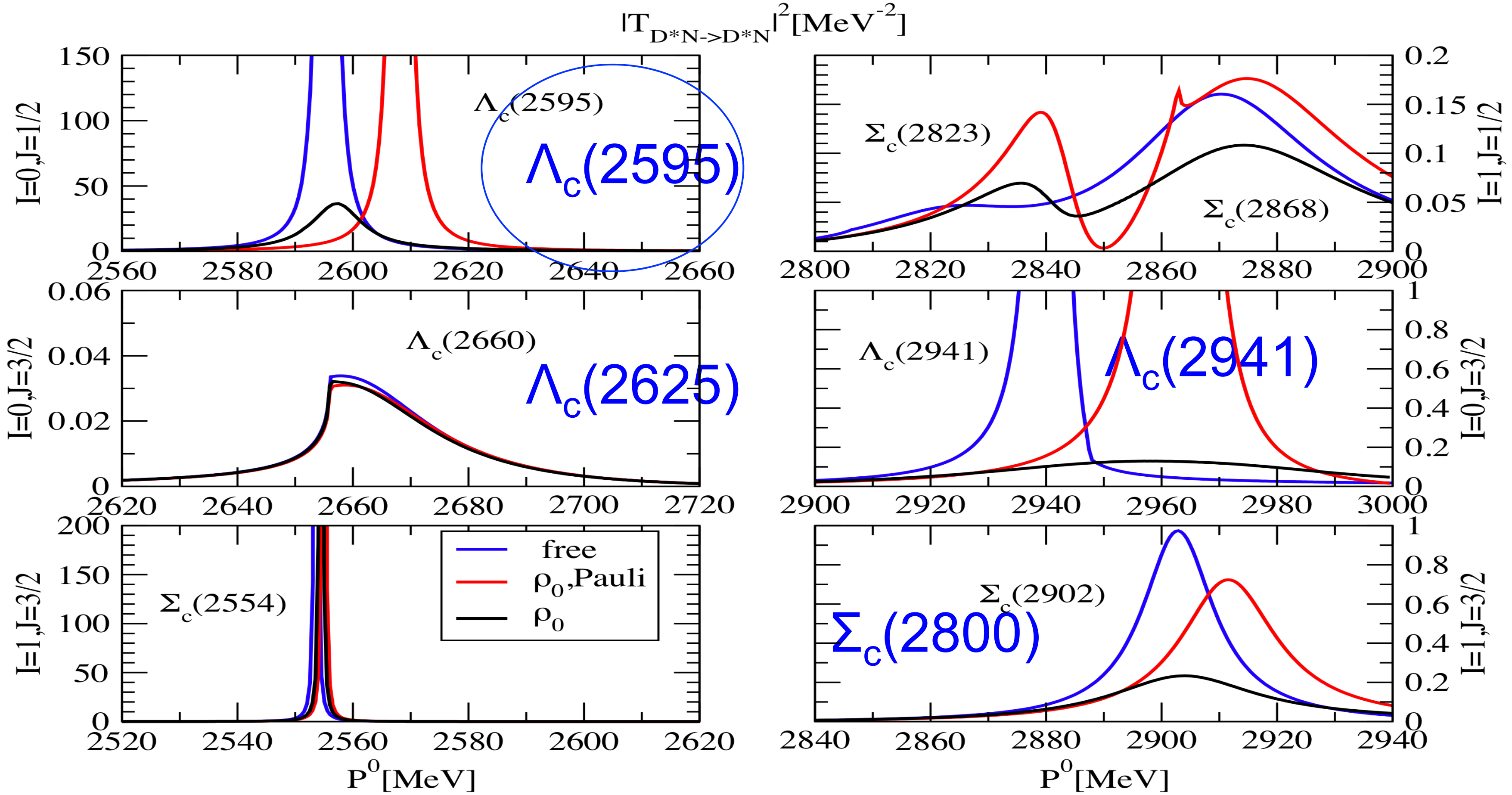
PDG

| Resonance | $I(J^P)$ | Status | Mass [MeV] | $\Gamma$ [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 $\Sigma_c(2765)$ | | | | |
| $\Lambda_c(2880)$ | $0(5/2^+)$ | *** | $2881.53 \pm 0.35$ | $5.8 \pm 1.1$ |
| $\Lambda_c(2940)$ | $0(?^?)$ | *** | $2939.3 + 1.4 - 1.5$ | $17 + 8 - 6$ |
| $\Sigma_c(2800)^{++}$ | $1(?^?)$ | *** | $2801 + 4 - 6$ | $75 + 22 - 17$ |
| $\Sigma_c(2800)^{+}$ | $1(?^?)$ | *** | $2792 + 14 - 5$ | $62 + 60 - 40$ |
| $\Sigma_c(2800)^{0}$ | $1(?^?)$ | *** | $2806 + 5 - 7$ | $72 + 22 - 15$ |

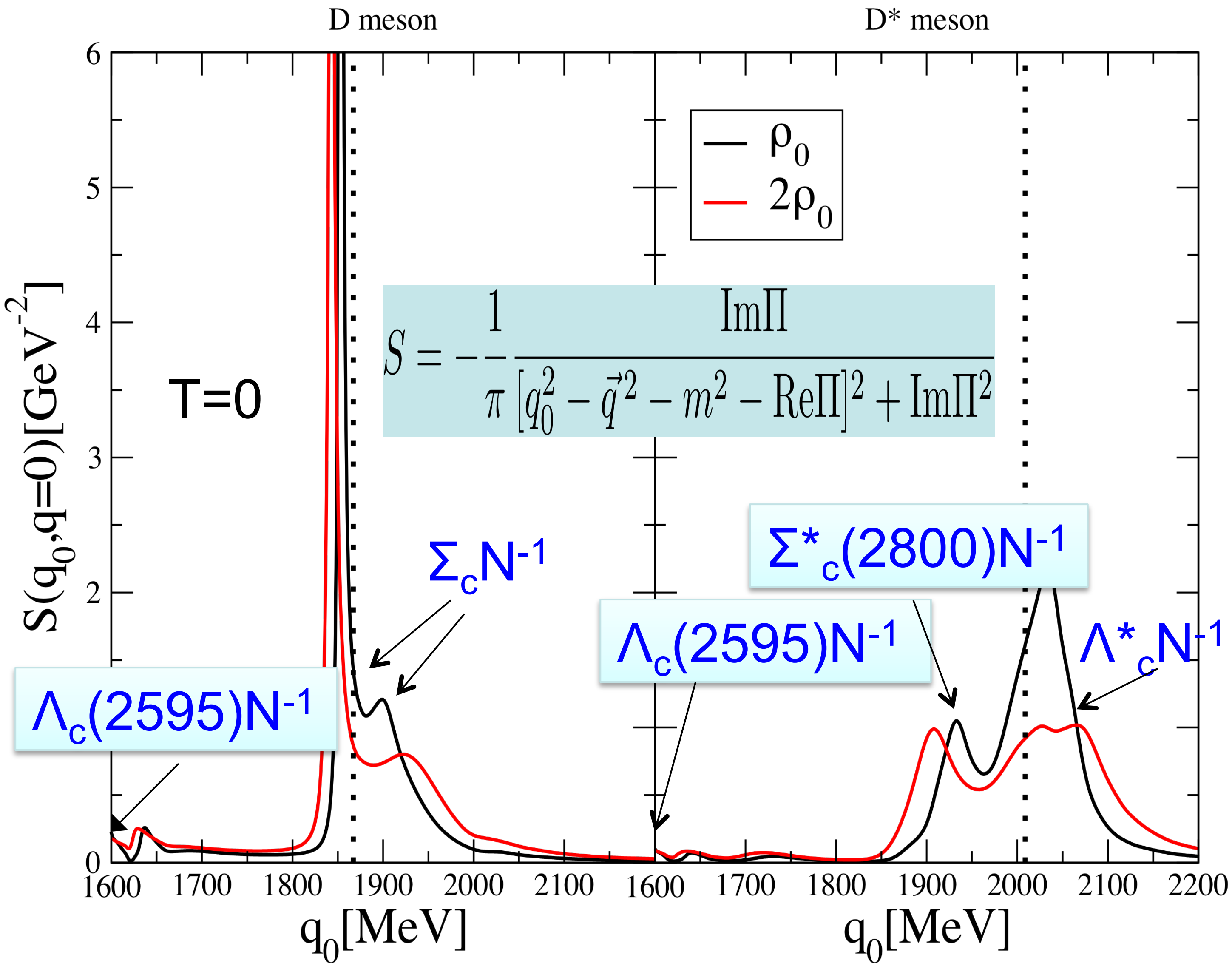
# Dynamically-generated baryonic resonances in nuclear matter

LT, Garcia-Recio and Nieves '10

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



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



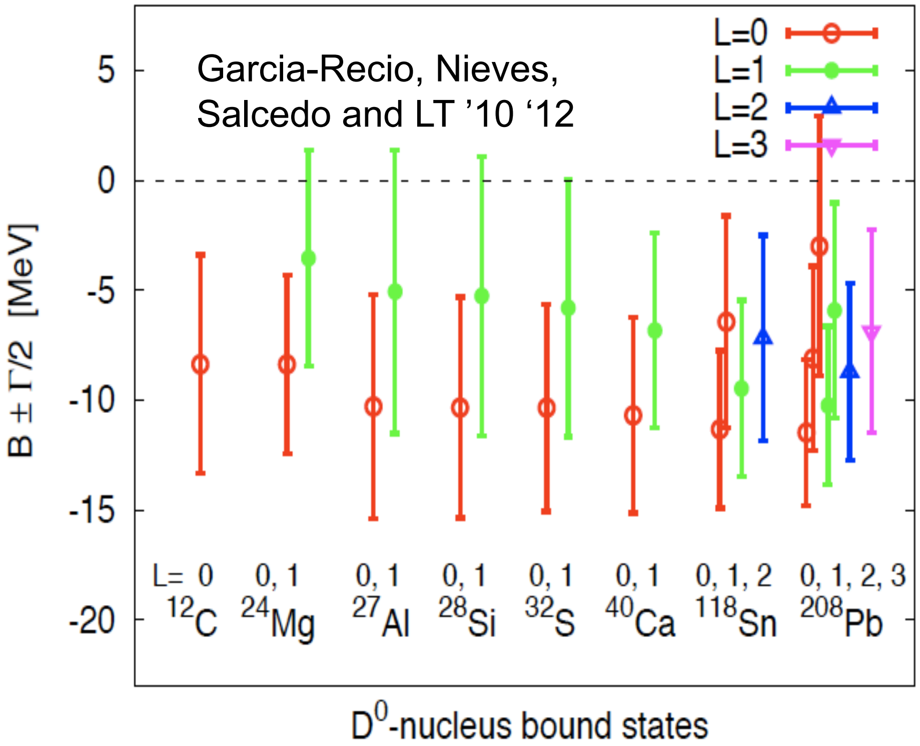

$$S = -\frac{1}{\pi}\frac{\mathrm{Im}\Pi}{[q_0^2 - \vec{q}^{\,2} - m^2 - \mathrm{Re}\Pi]^2 + \mathrm{Im}\Pi^2}$$

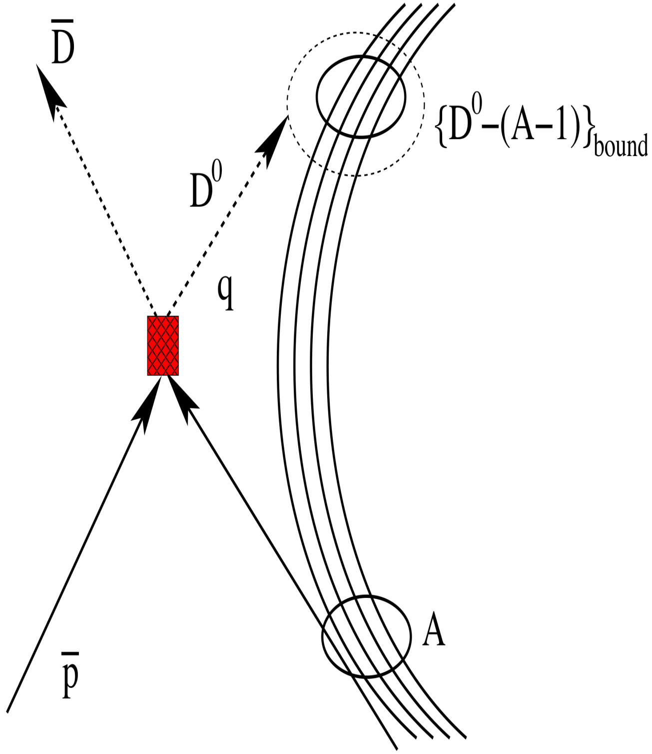
Simultaneous calculation of D and D* self-energies

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. '13
Garcia-Recio et al. '13

# D mesons in nuclei

Solving Schroedinger equation...




-Weakly bound $D^0$-nucleus states with important widths in contrast to QMC model, while $D^+$ does not bind

- $D^-$ and $D^0$ bind in nuclei

Experimental observation is, though, a difficult task

# 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

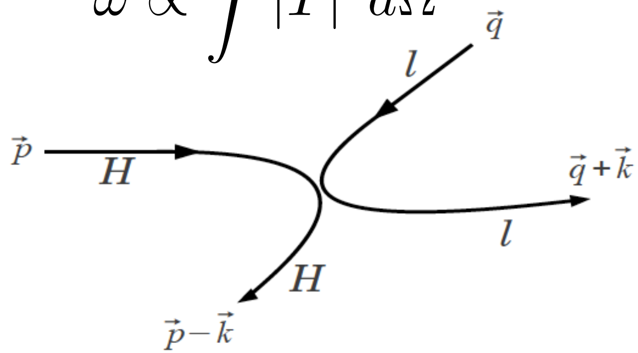
$$\frac{\partial f(t,\mathbf{p})}{\partial t} = \frac{\partial}{\partial p_i}\left\{F_i(\mathbf{p}) f(t,\mathbf{p}) + \frac{\partial}{\partial p_j}\left[\Gamma_{ij}(\mathbf{p}) f(t,\mathbf{p})\right]\right\},$$

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

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

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

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




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

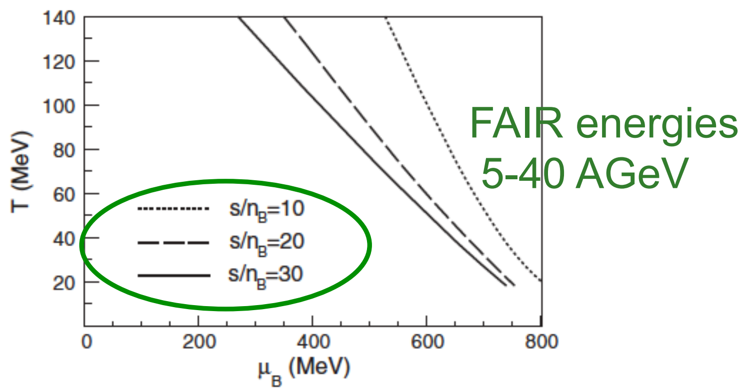
We need scattering amplitudes $|T|^2$

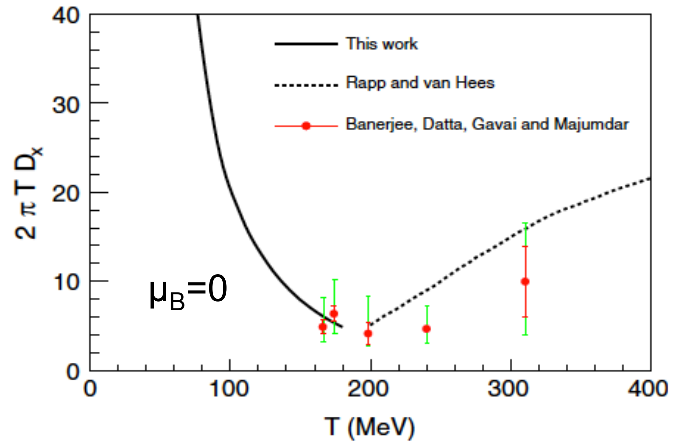
Abreu, Cabrera, Llanes-Estrada, Torres-Rincon '11;
LT and Torres-Rincon '13

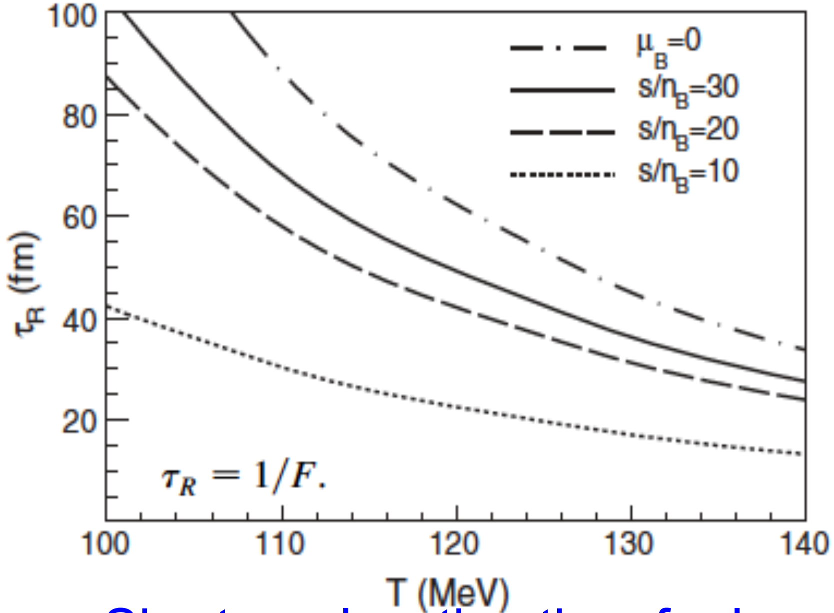
Talk by J.M. Torres-Rincon

# Some results for FAIR energies

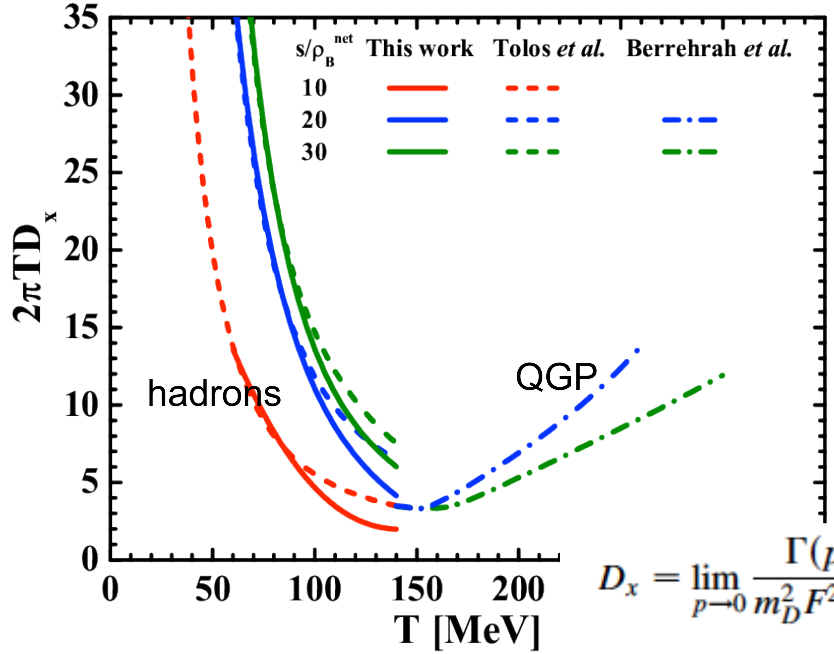
LT and Torres-Rincon '13




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



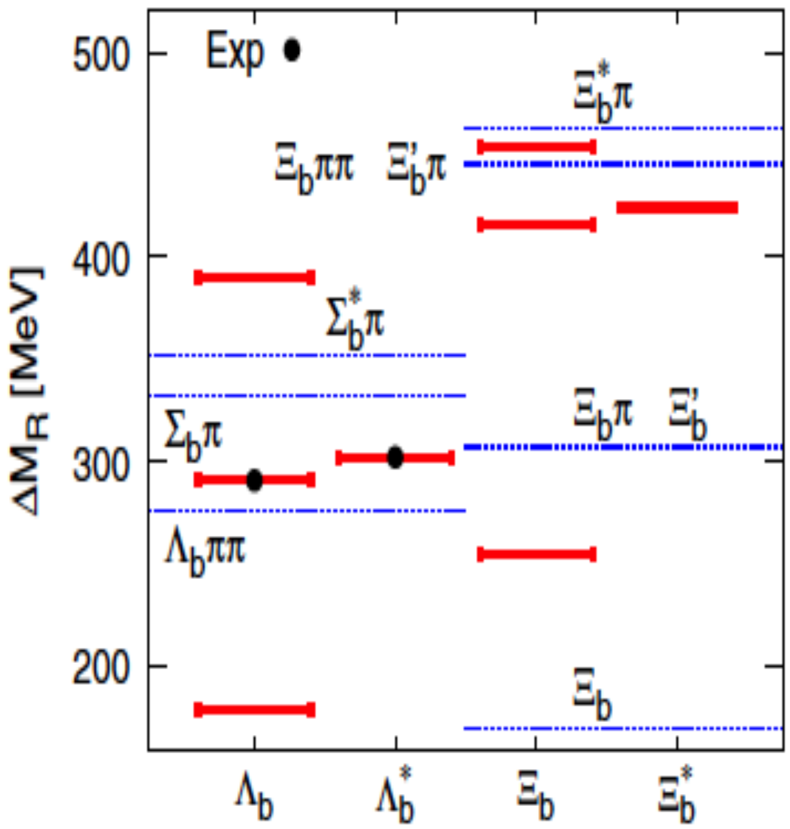

$$D_x = \lim_{p\to 0} \frac{\Gamma(p)}{m_D^2 F^2(p)}.$$

Continuous matching at $T_c$

Berrehrah et al. '14; Ozvenchuk et al (LT). '14

# Beauty under Extremes 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

# Compositeness of strange, charm and beauty Λ states

$$X_i = -\mathrm{Re}\left( g_i^2 \frac{dG_i}{d\sqrt{s}}\bigg|_{\sqrt{s_R}} \right)$$

$$Z = -\mathrm{Re}\sum_{i,j} g_i g_j \left( G_i \frac{\partial V_{ij}}{\partial\sqrt{s}} G_j \right)\bigg|_{\sqrt{s_R}}$$

$$1 = Z + \sum_i X_i$$

elementariness (Z) compositeness ($X_i$)

• same results for strange Λ: two $J^P=1/2^-$ and one $J^P= 3/2^-$ states

• $\Lambda_b$ bound states or narrow $\Lambda_c(2595)$ are well described as molecules

• wide $\Lambda_c(2595)$ and $\Lambda_c(2625)$ would require new mechanisms, such as d-wave interactions.

**charm**

| State | $J^P$ | $\sqrt{\alpha}$ | $M_R$ | $\Gamma_R$ | $1-Z$ | Channel | $\lvert g_i\rvert$ | $g_i$ | $X_i$ | $(X'_i)$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $\Lambda_c(2595)$ | $\frac{1}{2}^-$ | 1 | 2619.0 | 1.2 | 0.878 | $\pi\Sigma_c$ | 0.31 | $0.22+0.22i$ | $-0.012$ | $(-0.023)$ |
| | | (0.979) | (2592.3) | (0.3) | (0.844) | DN | 3.49 | $-3.49-0.14i$ | **0.275** | (0.292) |
| | | | | | | $D^*N$ | 5.64 | $-5.64+0.14i$ | **0.465** | (0.451) |
| $\Lambda_c(2595)$ | $\frac{1}{2}^-$ | 1 | 2617.0 | 90.0 | 0.401 | $\pi\Sigma_c$ | 2.36 | $2.09-1.09i$ | **0.325** | (0.252) |
| | | (0.950) | (2595.0) | (36.8) | (0.354) | $DN$ | 1.64 | $-1.46+0.75i$ | 0.027 | (0.015) |
| | | | | | | $D^*N$ | 1.43 | $1.34+0.51i$ | 0.024 | (0.057) |
| $\Lambda_c(2625)$ | $\frac{3}{2}^-$ | 1 | 2667.0 | 55.0 | 0.365 | $\pi\Sigma_c^*$ | 2.19 | $1.97-0.95i$ | **0.268** | (0.319) |
| | | (0.985) | (2628.1) | (0.0) | (0.405) | $D^*N$ | 2.03 | $1.96-0.51i$ | 0.057 | (0.044) |

**beauty**

| State | $J^P$ | $\sqrt{\alpha}$ | $M_R$ | $\Gamma_R$ | $1-Z$ | Channel | $g_i$ | $X_i$ | $(X'_i)$ |
|---|---|---|---|---|---|---|---|---|---|
| $\Lambda_b(5912)$ | $\frac{1}{2}^-$ | 1 | 5878.0 | 0.0 | 0.956 | $\pi\Sigma_b$ | 0.04 | 0.000 | (0.000) |
| | | (1.01) | (5912.1) | (0.0) | (0.958) | $\bar{B}N$ | $-4.55$ | **0.205** | **(0.217)** |
| | | | | | | $\bar{B}^*N$ | $-7.70$ | **0.539** | **(0.561)** |
| $\Lambda_b(5912)$ | $\frac{1}{2}^-$ | 1 | 5949.0 | 0.0 | 0.865 | $\pi\Sigma_b$ | 1.31 | **0.698** | **(0.397)** |
| | | (0.984) | (5912.0) | (0.0) | (0.788) | $\bar{B}N$ | $-2.90$ | **0.096** | **(0.215)** |
| | | | | | | $\bar{B}^*N$ | 1.91 | 0.038 | **(0.082)** |
| $\Lambda_b(5920)$ | $\frac{3}{2}^-$ | 1 | 5963.0 | 0.0 | 0.818 | $\pi\Sigma_b^*$ | 1.54 | **0.581** | **(0.356)** |
| | | (0.983) | (5919.7) | (0.0) | (0.785) | $\bar{B}^*N$ | 4.16 | **0.185** | **(0.319)** |

Garcia-Recio, Hidalgo-Duque, Nieves, Salcedo and LT ‘15

# B meson propagation in dense hot matter

Fokker-Planck equation

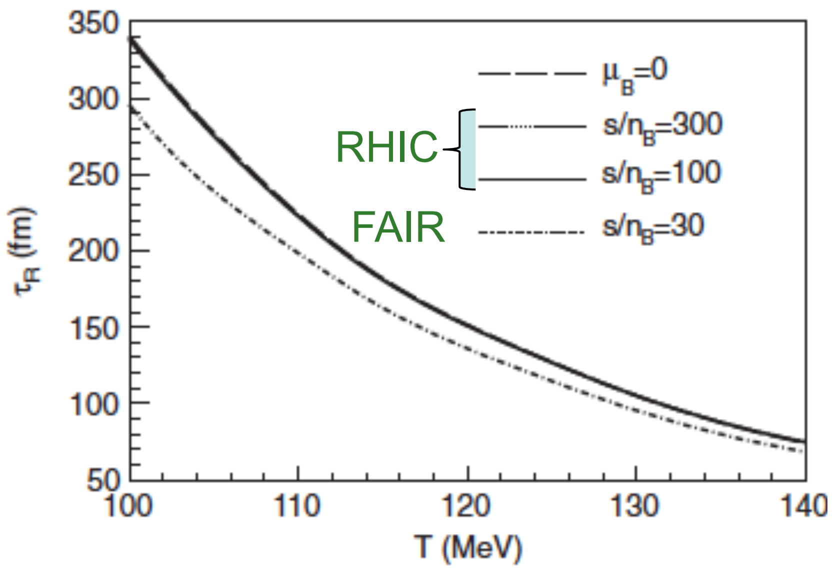
Talk by J.M. Torres-Rincon

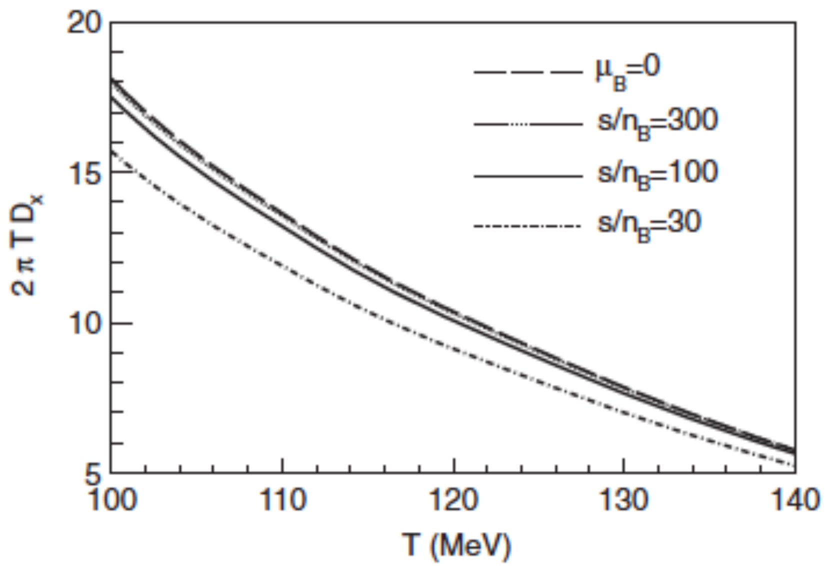
$$\frac{\partial f(t,\mathbf{p})}{\partial t} = \frac{\partial}{\partial p_i}\left\{F_i(\mathbf{p}) f(t,\mathbf{p}) + \frac{\partial}{\partial p_j}[\Gamma_{ij}(\mathbf{p}) f(t,\mathbf{p})]\right\},$$

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
HadronPhysics3
01 Grant Agreement

MARIE CURIE ACTIONS